

**Energy Research and Development Division
FINAL PROJECT REPORT**

**AUTOMATED ROOFTOP
AIR CONDITIONING FAULT
DETECTION IN RETAIL STORES AND
EXTENSION OF LEARN HVAC**

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Prepared by: Lawrence Berkeley National Laboratory With Assistance from:
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PREFACE

The California Energy Commission's Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Automated Rooftop Air Conditioning Fault Detection in Retail Stores and Extension of Learn HVAC is the final report for the Automated Rooftop Air Conditioning Fault Detection in Retail Stores and Extension of Learn HVAC project (contract number CEC-500-06-046) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

This project had two key results. The first was developing a new method for detecting faults in the operation of the heating, cooling and economizer subsystems of rooftop air-conditioning units. Improved fault detection will reduce energy consumption and increase energy efficiency, which will reduce greenhouse gases and other air emissions that contribute to air pollution. The method employed techniques from signal processing and time series analysis to evaluate the correlation among measuring parameters and to assess the presence or absence of faults in the system. Limited testing using measured time-series performance data from rooftop units on “big box” retail stores indicated that the method can detect some major faults with essentially no configuration effort and no additional sensors and can do so when equipment is cycling rather than being in steady state. The description of the method has been submitted for publication in ASHRAE’s *International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research* and will be discussed with members of the Department of Energy’s Commercial Building Energy Alliance and with other stakeholders.

The second result was enhancing the Learn HVAC software program by adding new functionality and capabilities. The new Learn HVAC 2.0 software will strengthen the knowledge and skills of workers who operate and maintain heating, ventilation, and air conditioning systems. Learn HVAC was enhanced by adding energy and peak demand capabilities as well as integrated whole building energy simulations using EnergyPlus, a whole building energy simulation program. Learn HVAC 2.0 also has new heating and cooling plant components, a refined equation-based simulation model and several other refinements. The next steps are completing the HVAC 2.0 beta version to facilitate testing and preliminary field use, completing the final version of HVAC 2.0, and developing the next version of the software and associated training tools.

Key Words: Air conditioning, Rooftop units, Retail stores, Fault detection, Technicians, Building operators

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EXECUTIVE SUMMARY

Introduction

Over half of the commercial-building cooling energy consumption in the United States is provided by rooftop package air conditioners and other heating, ventilation, and air-conditioning (HVAC) devices that provide combined heating and cooling. These devices are especially prevalent in small commercial buildings and retail stores. Many of these buildings fail to fulfill their technical potential in terms of energy consumption, indoor environmental quality, and equipment lifetime. A major cause of this underperformance is operational faults and problems that often go undetected for significant periods of time, particularly if their major impact is on energy consumption. These operational faults and problems arise from poor design, poor installation, a lack of commissioning—especially functional testing, poor maintenance, and an inability to detect and diagnose faults and problems on the part of building operators and/or service technicians. Unlike large HVAC systems that have dedicated building operators who are responsible for daily operation and maintenance, rooftop units are typically installed in buildings where owners are more cost-sensitive and tend to have limited budgets for operation and troubleshooting problems. Although most rooftop units are mass-produced and seldom have any design faults or product defects before installation, faults can be introduced during installation or can develop over the operating life of the unit. In addition, digital control technology and advanced security systems are becoming more common in HVAC systems, necessitating a new skill set for system operators.

Until recently, available technologies for online fault detection and diagnostics (FDD) have been very limited, and most troubleshooting is performed manually. Manual troubleshooting is not cost-effective or efficient. Automated analysis and visualization tools to improve FDD have the potential to reduce energy use, improve indoor environmental quality, and extend the lifetime of these units.

Project Purpose

There were two overall goals of this project. The first was to develop automated diagnostic software to provide rooftop air conditioning unit fault detection, improve the overall performance of rooftop units in retail stores in California, and reduce the peak demand and energy bills for retail stores across the state. The second goal was to develop computer-based training methods and software that could be used to train future installers, service technicians and operators of HVAC equipment to improve their understanding of and ability to diagnose and solve operating problems when they occur. The first objective of the project was developing methods to automate diagnosis of faults in rooftop units and to successfully test these methods on rooftop units in Target stores. The second objective was enhancing the Learn HVAC software for HVAC systems by improving the functionality of the software and adding key energy analysis capabilities, and then testing the enhanced software as an educational tool in community colleges. Learn HVAC was previously called HVAC ePrimer.

Project Results

The approach used for developing methods to automate diagnosis of faults in rooftop units in retail stores leveraged a previous collaboration between the Lawrence Berkeley National Laboratory (LBNL) and Target (Haves et al. 2008). A new method was developed for monitoring the operation of the heating, cooling and economizer subsystems of rooftop air-conditioning units and detecting and, in the case of some types of fault, diagnosing a variety of fault conditions. The method employed techniques from signal processing and time series analysis to evaluate the correlation among measuring parameters and to assess the presence or absence of faults in the system. Limited testing using measured time-series performance data from rooftop units on “big box” retail stores indicated that the method can detect some major faults with essentially no configuration effort and no additional sensors and can do so when equipment is cycling rather than being in steady state. This method is not dependent on high accuracy models, has systematic solutions for measurement constraints, and, importantly, does not have the limitation of using data measured in a steady-state condition. The method is limited in scope but is potentially complementary to existing FDD methods for rooftop units, although further work is required to clarify this issue.

The description of the method has been submitted for publication in ASHRAE’s research journal, the *International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research*. The response to this paper will provide one indication of the commercialization interest. The method will also be discussed with members of the U.S. Department of Energy’s Commercial Building Energy Alliance and with other researchers and stakeholders. The commercialization potential is not clear at this stage, but because of its limited scope, it is unlikely to have significant potential unless it can be combined with other complementary methods. The authors recommended that this general problem and the method developed during this project be discussed with the various stakeholders to determine the current relevance of and interest in the method in light of developments in the field that have occurred since the completion of the active research phase of the project.

The approach used for enhancing Learn HVAC involved developing, refining, enhancing, and distributing open-source, free software products to provide substantial computer-based resources and tools for assisting in workforce development. The areas to be addressed were HVAC system operation, controls and troubleshooting, lighting, envelope, controls, and the whole building integrated design and operation of low-energy, sustainable buildings. This work built on previous collaborations among SuPerB, LBNL and others that was funded by the National Science Foundation Advanced Technological Education program. The existing Learn HVAC 1.0 software was primarily intended to help community college students and others acquire the skills they need in order to commission and operate high-performance buildings, with emphasis on Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) equipment and control systems.

The major result for the Learn HVAC portion of the project was adding important energy and peak demand analysis capabilities to the educational software tool Learn HVAC 1.0. In addition to these new capabilities, the new alpha version of Learn HVAC 2.0 version includes integrated

whole building energy simulations implemented using EnergyPlus. EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model energy and water use in buildings. These simulations include selected easy-to-use inputs to EnergyPlus, a macro-driven EnergyPlus prototypical office building, selected graphical outputs from EnergyPlus, and the ability to include two EnergyPlus simulations within any scenario. The new version of the software also has new heating and cooling plant components (boiler, chiller, cooling tower), a refined equation-based component simulation model with documentation of model operation, refinements to the control structure used for the HVAC system, and refinements to several Learn HVAC user interface features. Learn HVAC 2.0 will allow students to understand the principles underlying both the design and operation of efficient systems and to diagnose the causes of inefficient operation. It will also help members of the building industry in California to better understand how energy-efficient HVAC systems work and how to troubleshoot systems that are not working properly.

The pre-alpha version of Learn HVAC 1.0 has been available online since 2008, without advertisement. During this time several thousand people worldwide have downloaded the software and very positive feedback has been provided. From this experience, the authors anticipated that the more robust features of Learn HVAC 2.0 will encourage its widespread use by numerous students, instructors, and interested persons. Its potential widespread use is enhanced because it is available for free and major elements are available under Open Source License Version 3 (OSLv3).

The authors' recommendations included completing the beta version of Learn HVAC 2.0, which will provide an adequate platform for widespread testing and preliminary use in the field throughout California as well as other locations in the country; completing the final production version of Learn HVAC 2.0., and developing a more comprehensive Learn HVAC 3.0 version. Learn HVAC 3.0 would include numerous new features, systems, and modules, and would address the needs of a much broader set of user types. The anticipated project results included a comprehensive interactive set of training tools for troubleshooting of several important commercial building energy-related systems and components including HVAC, lighting, building envelope, and daylighting.

Project Benefits

Cooling by rooftop units accounts for a significant fraction of the electricity consumption and peak demand in California. In general, detection and correction of faults and operational problems results in improved efficiency, adequate capacity, or a combination of the two. This in turn results in reduced energy consumption, improved indoor environmental conditions, or both. The fault detection method developed in this project has the potential to reduce energy consumption, which will reduce greenhouse gas emissions and other air emissions that contribute to air pollution, as well as improve indoor air quality for California residents who work in commercial buildings.

Many HVAC systems in California do not provide the thermal comfort they were designed to provide, and they often use much more energy than intended. Improved understanding of how

HVAC systems should work will help California improve the comfort conditions in its commercial building stock, thus improving productivity, and improve the energy efficient operation of many HVAC systems via improved understanding by building operators and operations and maintenance (O&M) technical staff.

Commercial buildings in California consume approximately 67,000 gigawatts per year of electricity and approximately 1,300 megatherms per year of natural gas (one therm is equal to 100,000 British thermal units). HVAC systems contribute approximately 28 percent of the entire electricity consumption and about 38 percent of the gas consumption. The authors estimated that improving the knowledge and skills of HVAC operators and maintenance personnel could result in a 10 percent savings from improved delivery of new buildings and retrofitted buildings as well as a 10 percent savings from the improved operational efficiency of the buildings.

It is also increasingly accepted that the biggest barrier to the achievement of California's long-term building energy performance goals is the lack of a sufficiently skilled workforce. The number one goal of the Workforce Education and Training element of the California Public Utility Commission's Strategic Plan is to establish energy efficiency education and training at all levels of the state educational system. There is currently a very high demand in the industry for technicians with good education and training, particularly controls technicians. Commissioning agents and design engineers with strong backgrounds in building energy performance are also in short supply, particularly in California. The training aspects of the program described in this report are intended to transform commercial building maintenance and operations in California. The software development projects will make an immediate impact to California by providing an alternative mechanism for enhanced building delivery and operations through training building technicians, operators, building managers, designers, contractors, and energy service providers. The software has the potential to reach a much larger audience much faster than classroom training alone.

The improved education and training from an advanced suite of educational software could substantially improve the distribution and depth of knowledge and skills in the workforce about energy efficiency and could thus help to transform both the delivery and the operations and maintenance of commercial buildings in California.

1.0 Introduction

Many buildings fail to fulfill their technical potential in terms of energy consumption, indoor environmental quality, and equipment lifetime. A major cause of this underperformance is operational faults and problems that often go undetected for significant periods of time, particularly if their major impact is on energy consumption. These operational faults and problems arise from poor design, poor installation, a lack of commissioning, esp. functional testing, poor maintenance, and an inability to detect and diagnose faults and problems on the part of building operators and/or service technicians. A two-pronged approach to this situation was adopted in the project reported on here:

- Develop automated diagnostic software to compensate, partially, for the lack of skill and/or availability of building operators
- Develop computer-based training methods and software for future installers, service technicians and operators

This project consisted of two main tasks:

1. Automated Rooftop Air Conditioning Unit Fault Detection , and
2. Enhancing the Learn HVAC¹ Educational Software for Heating Ventilation and Air Conditioning (HVAC) systems.

The first task focuses on simple fault detection methods for the most common type of HVAC equipment, i.e. rooftop package air conditioners. The second task involves the extension of the Learn HVAC e-learning software initially developed for use in two-year college programs.

1.1. Problem Statement for FDD for Rooftop Units

Rooftop package air conditioners and other unitary HVAC devices are used extensively for commercial building cooling and heating in US, especially for small commercial buildings and retail stores. The cooling energy usage by these units represents over half of the US commercial-building cooling energy consumption. However, roof top units are often poorly maintained, monitored, and prone to faults. Unlike large built-up HVAC systems, most of which have dedicated building operators who are responsible for daily operation and maintenance, rooftop units are typically installed in buildings where owners are more cost sensitive and tend to have tight budgets for operation and troubleshooting.

Most rooftop units are mass-produced and therefore they seldom have any design faults or product defects before installation. However, faults can be introduced during installation or can

¹ N.B. The HVAC ePrimer training software has been renamed Learn HVAC, and will be referred to by that name in the remainder of this report.

develop over time during operation. Degradation faults can go undetected until they start to create serious comfort problems. Faults can not only result in large energy waste but also can shorten equipment life, causing catastrophic equipment failure later on. Typical hardware faults include dampers, dirty/clogged filters and coils, incorrect refrigerant charges and drifted sensors. Sometimes, energy waste can be caused by faulty control or operation. For example, actual operating hours can deviate considerably from the intended or the original schedule.

However, until now, available technologies for online fault detection and diagnostics (FDD) have been very limited and, most of the time, troubleshooting is still performed manually. One technical difficulty is that rooftop units are typically poorly instrumented and the cost associated with adding more sensors to these units can be high relative to the cost of the unit. Conventional monitoring methods and FDD tools for built-up systems are not applicable to rooftop units with Direct Evaporator Cooling (DX) and direct-fired heating.

Such rooftop units are widely used in retail stores. In general, retail stores have no engineers or technicians dedicated to HVAC operation at each site. Those companies that collect performance data typically collect them remotely through a network and store them in a central database at the company headquarters. If a fault occurs in a store and starts to cause problems, the store manager will contact the engineers at the headquarters and they will typically manually retrieve the data from the database and identify the problem. Relatively few data points are trended and only the previous 24 hours of data are saved in the database.

As with many other engineers and operators, when the engineers responsible for the operation of retail chain stores analyze data and check for any suspicious activities, they have to either read the data in text or plot them manually in a spreadsheet or use other visualization tools embedded in the control system. In the current process, the energy related faults could be undetected for a long period of time, resulting in substantial energy waste. Manual troubleshooting is not cost effective and the engineers need some automated analysis and visualization tools to improve their productivity and the accuracy of the fault diagnosis.

1.2. Problem Statement for Adding Energy to Learn HVAC

Building HVAC systems and controls are becoming increasingly complex, digitized, and difficult to properly design, construct, operate, maintain, and troubleshoot. Building operators and technicians today must master new computer-based technologies in addition to their traditional skills. Many buildings are not operating properly, thus providing marginal or poor comfort and quality, while using much more energy than needed. In many cases the energy savings in the building fall far short of the savings promised by the use of advanced technologies. Several major trends are increasing the complexity and difficulty of properly operating and maintaining buildings.

Digital control technology is becoming pervasive on both new and existing buildings. Thus, building operators and technicians must master a new set of computer-related skills (e.g., hardware, software, database management, and local area networking) in addition to their traditional skills of HVAC management and repair.

Regulations and policies are increasingly involved, including new commissioning and sustainability factors.

Energy performance monitoring, commissioning, and retro-commissioning address increasing energy costs but require advanced capabilities to be effective.

Security is increasingly important since 9/11 and operators must monitor advanced security systems, initiate emergency response plans, and shut down complex systems in the event of environmental attacks.

Saving energy in buildings involves more than just installing energy efficient equipment. High efficiency equipment that is not properly installed, calibrated, tested, operated or maintained will likely save far less energy than anticipated. Thus, saving energy also involves training skilled people to design, construct, operate, and maintain the increasingly complex buildings and systems.

One path to improved building performance is to raise the level of understanding of (1) proper, energy-efficient HVAC operations and controls on the part of building operators and technicians, and of (2) proper system-level troubleshooting methods and approaches to solve problems when they occur. The proposed enhancements to the Learn HVAC educational software focus on teaching troubleshooting skills at the system-level, along with skills in communications and teamwork. Such skills will help operators and technicians in the field of building operations, maintenance and commissioning identify and rectify faults and operating problems that increase energy consumption and peak electricity demand.

A baseline version of Learn HVAC has been developed under a 3-year grant from the National Science Foundation and is designated as Learn HVAC 1.0. The tools use 3D animations of accurate simulations to teach HVAC technicians how to better operate, maintain and troubleshoot increasingly complex, digitized HVAC systems and controls in buildings. The software is using the latest technical education approaches being promoted by the National Science Foundation's Advanced Technological Education (ATE) program. Demonstrations and tests with both community college and high school students indicate that the current software works well and is effective.

The Learn HVAC is an open source package that is intended to be available free primarily to students and instructors at community college HVAC programs, but also to potential users throughout the buildings industry.

1.3. Project Objectives for FDD for Rooftop Units

The overall technical goal of this task was to develop technology to improve rooftop unit performance. The specific, technical objectives were to:

- Develop methods that can automate diagnosis faults in rooftop units.

- Successfully test the method with rooftop units in Target stores.

The overall economic/cost goal of this task was to reduce the cost of operation of HVAC systems in California. The specific, economic/cost objective was to:

Develop and demonstrate the potential to improve the overall performance of rooftop units in retail stores in California, reducing the peak demand and the energy bills for retail stores across the state.

1.4. Project Objectives for Adding Energy to Learn HVAC

The overall technical goal of this task was to improve building control training and operators skill. The specific, technical objectives were to:

Improve the functionality of the Learn HVAC 1.0 software.

Add key energy analysis capabilities to the Learn HVAC 1.0 software.

Work with community colleges and test the tool in education.

The overall economic/cost goal of this task was to reduce the cost of operation of HVAC systems in California. The specific, economic/cost objective was to:

Develop and demonstrate the potential to improve the knowledge and experience of building operators and thereby improve overall building performance in California and reduce energy consumption.

1.5. Overview of Pre-existing FDD Methods and Tools

Automated fault detection and diagnosis involves the use of software tools to analyze the behavior of a building, determine if the performance is unsatisfactory (fault detection), and then isolate or localize the fault in order to facilitate repair (fault diagnosis). The behavior may be observed in the course of an active functional test performed by the tool or in the course of passive monitoring of routine operation.

Performance monitoring involves continuously measuring the behavior of the building in order to assess its performance. Issues include the provision of the necessary sensors and data acquisition, storage, retrieval and visualization. It also includes the role of human intelligence in assessing performance.

Commissioning typically involves active testing of components and sub-systems as one of its core activities, although it also includes a systematic series of activities, starting in the planning phase, aimed at ensuring correct operation of the building. Commissioning is currently a manual activity involving specific tests that are performed and analyzed by specially trained engineers. **Automated commissioning**, which is a relatively new research topic, is based on active functional tests performed and analyzed by an automated fault detection and diagnosis tool.

There has been a significant amount of work in the field of automated diagnostics for HVAC systems - see Katipamula and Brambley (2005a, 2005b) for a review of progress up to 2004.

However, most of the effort has been focused on built-up systems that use hot and chilled water (e.g. House et al. 2001, Schein and House 2003, Xu et al. 2005, Haves et al. 2007) rather than direct expansion (DX) coils for cooling and direct fired coils for heating. Diagnostic methods for DX vapor compression cooling systems have been developed by Breuker *et al.* (2000) and by Li and Braun (2003). FDD systems are presumed to have a beneficial effect on energy consumption and complaints, though there is insufficient information currently available to allow the expected magnitude of this effect to be quantified. One issue is that FDD systems are only effective if action is taken in response to a positive fault detection.

Generally speaking, system faults can be divided into two categories; abrupt faults and degradation faults. Abrupt faults happen essentially instantaneously, with no advance warning from conventional sensors, while degradation faults evolve over time, becoming progressively more severe. In general, degradation faults do not result in catastrophic failure, though they can have serious consequences.

Any ideal diagnostic solution for RTU's should have the potential for large-scale implementation with minimal initial configuration requirement. Most current methods do not possess such characteristics. Some methods require measurements that do not exist in real applications. Some depend on accurate models or models that require extensive training data (high-quality data), which requires a substantial initial configuration effort. On the other hand, when more simplified models are used, the new challenge is how to differentiate between modeling/ measurement errors and system malfunctions. These issues have been addressed by Haves et al. (2007), Najafi et al. (2010a), Schein et al. (2006), and Dexter and Ngo (2001). For example, in (Haves et al. 2007, Haves et al. 1996, Salsbury et al. 1995, Xu et al. 2005), Haves et al. developed a fuzzy-based mechanism for model-based diagnostics of air handling units. In (Najafi et al. 2008a, Najafi et al. 2010b), Najafi et al. employed the idea of analyzing behavioral patterns instead of residuals to loosen the requirement for accurate models. Another approach is rule-based diagnostics, in which the rules implicitly simulate some qualitative or semi-quantitative aspects of the system (Youk et al. 2007, Schein et al. 2006, Dexter and Ngo 2001, Ngo and Dexter 1999).

Another issue with diagnostic solutions based on simplified models is steady-state conditioning. These models are usually limited to simulating the static behavior of the system; consequently, that measurement should be obtained when the system is in the steady-state condition. A typical strategy is to wait until the variations in the relevant variables are small enough to approximate steady state conditions. However, steady-state conditions may not occur frequently, because of cycling during routine operation, high frequency disturbances, or control loop oscillation.

In the light of these considerations, a simple statistical approach for rooftop unit diagnostics has been developed. The proposed solution does not depend on a detailed model, it does require steady-state conditions, and it can deal systematically with measurement constraints. By analyzing the correlation among variables and comparing them with the predictions of various

hypotheses, the diagnostic framework locates the pattern that best matches the data and evaluates the performance.

1.6. Overview of the Baseline Educational Software - Learn HVAC 1.0

A pre-alpha version of Learn HVAC 1.0 was developed under an NSF grant that ended in mid-2007. Demonstrations and early field-tests with both community college and high school students indicated that the software worked well and was effective. Its dissemination has been supported by the Institute for the Sustainable Performance of Buildings (SuPerB) and by LBNL. It may be downloaded at no cost from www.learnhvac.org.

The version of the software that existed in 2007, at the beginning of this Energy Commission project, had a highly graphical interaction with a virtual HVAC system and a single short term time horizon that permitted a user to interact with an accurate, second-by-second simulation of a generic HVAC system and the dynamics of its controls. The system was coupled to a series of 3D animations that present its performance in a visually realistic way. The 3D animations displayed air and water movement using colors to represent temperatures and the 3D graphic presentations are updated every few seconds by output information from the simulation running in the background. Key numerical data from the simulation was superimposed on each of the 3D views, and additional numerical data was presented within input and output panels on the graphic user interface (GUI). Simple time series charts were displayed reflecting system behavior, and the user could select and display additional time series charts and X-Y charts. Learn HVAC users could gain a basic understanding of how generic HVAC systems work, both when they are operating normally and when one or more “faults” are causing the system to operate outside of normal parameters.

The Learn HVAC 1.0 NSF-funded version focused on the operation of air-handling systems. That version did not address primary energy conversion equipment, and it did not include the ability to assess the energy impacts of HVAC system operations.

A pre-Alpha version of Learn HVAC 1.0 was posted on the www.learnhvac.org website in the summer of 2008, and has been available for free public download of the client software, including several scenarios. No advertising has been done about the availability of this version. To date some 4000 people have downloaded this version. Very positive feedback was received from as far away as South Africa and New Zealand. Several university faculty members and directors of company in-house education programs have requested access to the tool in order to use it as part of their educational programs.

The user of Learn HVAC 1.0 could examine a number of system or component level views of an air handling unit (AHU), including:

- Entire system including the conditioned space

- Mixing box & economizer

- Filter

Heating coil

Cooling coil

Fan

VAV box with reheat, and diffuser

Each view showed an animation plus a series of panels that permitted a user to view or change input values and fault conditions for the view or component.

An overview of the HVAC system model and its main components is shown in Figure 1.6.1-1. The goal of the HVAC system is to maintain room temperatures within each thermal zone within the desired range during both occupied and unoccupied periods.

The HVAC system is in typical office building with simple thermal zoning: a top floor, a bottom floor, and one or more middle floors. Each floor has just 5 thermal zones.

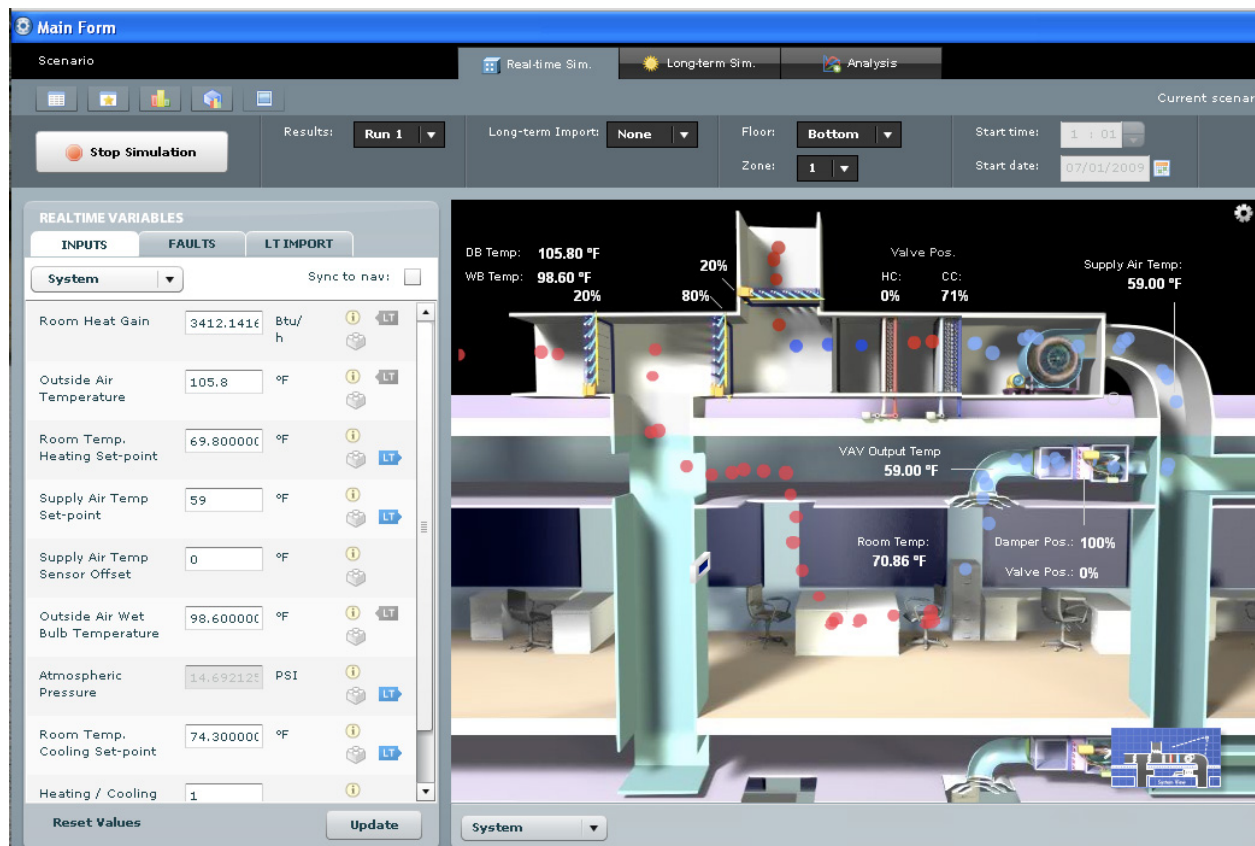


Figure 1.6.1-1: System level view

The mechanical components shown in Figure 1.6.1-1 are shown diagrammatically below in Figure 1.6.1-2. Each component is described in the Appendix, along with the sensors, actuators, and controllers.

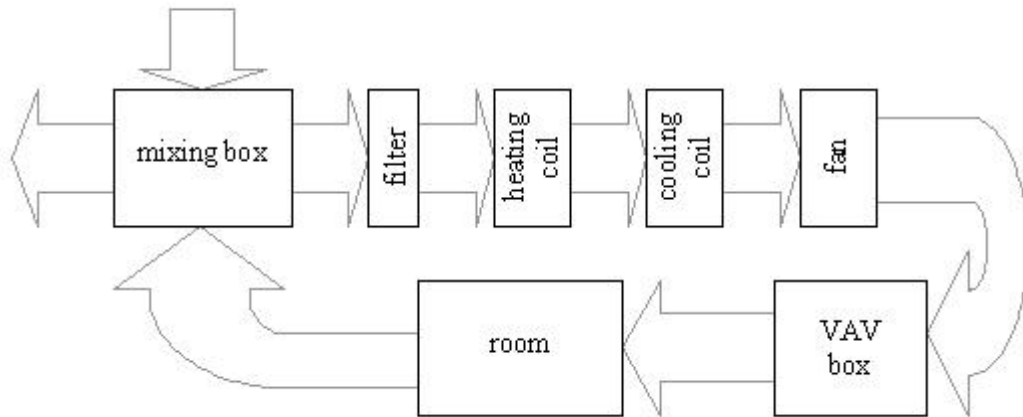


Figure 1.6.1-2: Overview of HVAC system model

2.0 Project Approach

2.1. Approach for FDD for Rooftop Units

The FDD for Rooftop Units task focuses on rooftop units in retail stores and leveraged a previous energy efficiency collaboration between LBNL and Target (Haves et al. 2008). The starting point was to develop a method to automate the fault detection process for rooftop units, implement it in a software tool and test it in Target Stores. A statistical framework for rooftop unit diagnostics was developed. This approach is not dependent on high accuracy models, has systematic solutions for measurement constraints, and, importantly, does not have the limitation of using data measured in a steady-state condition. The approach employs techniques from signal processing and time series analysis to evaluate the correlation among measuring parameters and assess the presence or absence of faults in the system. The methods developed have been disseminated by publishing in journals and conference papers.

2.2. Approach for Adding Energy to Learn HVAC

For the Learn HVAC task, the overall approach was to develop, refine, enhance, and distribute open-source, free software products to provide substantial computer-based resources and tools for assisting in workforce development. The areas to be addressed were HVAC system operation, controls and troubleshooting, lighting, envelope, controls, and the whole building integrated design and operation of low-energy, sustainable buildings.

The work accomplished within this specific project builds on previous collaborations among SuPerB, LBNL and others that were funded by the NSF Advanced Technological Education program. The existing Learn HVAC 1.0 software was primarily intended to help community college students and others acquire the skills they need in order to commission and to operate high-performance buildings, with emphasis on Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) equipment and control systems.

2.2.1. Key Target Audiences & Educational Settings for Learn HVAC 2.0

Key Target Audiences:

- Students and instructors in community colleges

- Students and instructors in four year colleges and universities

- Building operators, technicians, design professionals, commissioning providers and contractors

Key Target Educational Settings:

- As part of classroom lectures

- For individual and team problem-solving classroom exercises

- As part of seminars and workshops at energy centers

As part of instructor-assisted or directed online or hybrid courses

As part of online “virtual” team problem-solving exercises, where team members are either in the same location or are in different locations

For individual just-in-time, self-directed learning situations

The plan is to develop different functional variations of the Learn HVAC 2.0 educational software for different audiences at different levels.

3.0 Project Outcomes

3.1. Outcomes for FDD for Rooftop Units

The major project outcome for FDD for Rooftop Units was the development of a statistical framework for rooftop unit diagnostics. The approach employs techniques from signal processing and time series analysis to evaluate the correlation among measuring parameters and assess the presence or absence of faults in the system. This approach is not dependent on high accuracy models, has systematic solutions for measurement constraints, and, importantly, does not have the limitation of using data measured in a steady-state condition. The methods developed have been disseminated by publishing in journals and conference papers (Najafi et al. 2008a, Najafi et al. 2008b, Najafi et al. 2010a, Najafi et al. 2010b)

A schematic diagram of a rooftop unit is shown in Figure 3.1-1. Functionally, a rooftop unit is an air handling unit with built-in sources of heating and cooling. Usually, there are several stages of cooling and/or heating. Each stage can be thought of as an independent source of cooling or heating. When it is turned on, a certain amount of cool or heat is generated. The stages are activated sequentially by the controller to meet the load.

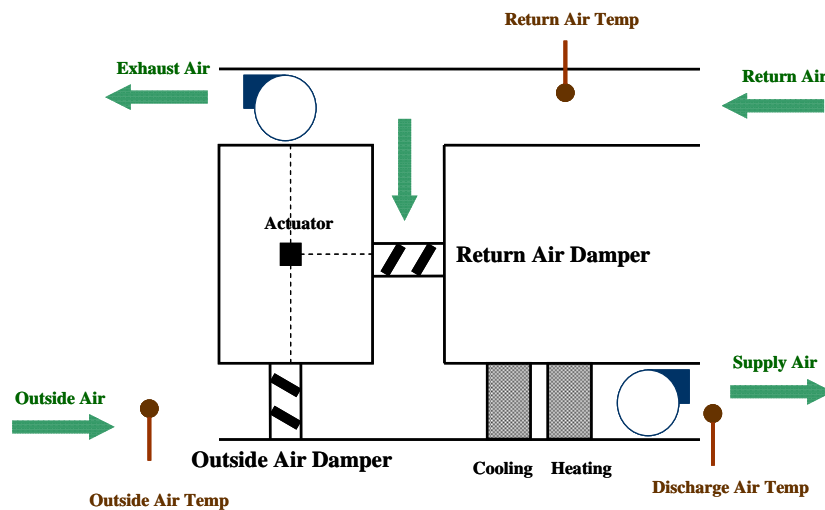


Figure 3.1-1: Rooftop unit schematic

Normally, a rooftop unit includes three temperature sensors: the outside air temperature (OAT) sensor, the return air temperature (RAT) sensor, and the discharge air temperature (DAT), and a fan status indicator. One of the main challenges in RTU (and air handling unit) diagnostics is the absence of a reliable measurement for the mixed air temperature (MAT)². This forces the use of the measurement of the discharge air temperature to analyze the mixing box performance,

²Sometimes, there is a temperature sensor between the mixing box and the coils to measure the mixed air temperature. However, due to incomplete upstream mixing, the sensor output has a bias that depends on the outside air fraction and is unreliable.

correcting for the temperature rise across the fan. However, as the DAT is also affected by any coil operation; the challenge is how to differentiate between the effects of the mixing box operation and the coil faults.

The functionality of the rooftop unit is evaluated in two steps:

1. Cooling/heating system diagnostics
2. Mixing box diagnostics

3.1.1. Cooling heating/system diagnostics

A common fault in rooftop unit is malfunctioning of the heating/cooling system, such that one or more stages are non-functional. One approach to detecting and isolating the faulty heating/cooling stage is to monitor the variations of the discharge air temperature (DAT). When the DAT does not respond as expected to a cooling or heating stage being commanded on or off, it is an indication of the coil malfunction. However, in practice, tracking coil response using DAT variations may not be straightforward. Usually, there is a delay between a control command and DAT response which complicates the observation, particularly when coils are turned on and off frequently to maintain the DAT set-point. One way to tackle the problem is to analyze the linear correlation between heating/cooling commands and DAT variations.³ The correlation function characterizes the relationship between the causes (heating/cooling commands) and the effects (DAT variations).

For each stage of heating and cooling, we assign a binary variable: $C_1, C_2, C_3, \dots, H_1, H_2, H_3, \dots$

$$C_i(t) = \begin{cases} -1 & \text{Cooling Stage } i \text{ is on} \\ 0 & \text{Cooling Stage } i \text{ is off} \end{cases} \quad H_i(t) = \begin{cases} 1 & \text{Heating Stage } i \text{ is on} \\ 0 & \text{Heating Stage } i \text{ is off} \end{cases}$$

The cooling/heating sum (CHS) is then defined as:

$$CHS(t) = C_1(t) + C_2(t) + \dots + H_1(t) + H_2(t) + \dots \quad (1)$$

When there is no fault, CHS and DAT should be strongly correlated. The correlation can be verified by analyzing the cross-correlation and cross-spectrum functions. For two series x_t and y_t , the cross-correlation function:

$$\gamma_{xy}(k) = E[(x_{t+k} - \mu_x)(y_t - \mu_y)] \quad (2)$$

where E indicates the expected value, μ_x and μ_y are the mean values of x_t and y_t respectively. The cross-spectrum, which is the Fourier transform of the cross-correlation, is:

³ Although the relation between heating/cooling commands and DAT variations is not completely linear, it is a reasonable assumption for diagnostic purposes, especially in drier climates. In particular, if the sensible heating or cooling rate generated by each stage of heating or cooling is approximately constant, independent of operating conditions, the linear approximation is adequate. $Q = hA(T_{coil} - T_{air})$, T_{coil} , h , and A are assumed to be constant, the relation between the air temperature (T_{air}) and heating/cooling command is linear.

$$f_{xy}(\omega) = \sum_{k=-\infty}^{\infty} \gamma_{xy}(k) e^{-i\omega k} \quad -1/2 < \omega < 1/2 \quad (3)$$

The cross-spectrum is a complex-valued function. The squared-coherence function, ρ , is then defined as:

$$\rho_{xy}^2(\omega) = \frac{|f_{xy}(\omega)|^2}{f_{xx}(\omega)f_{yy}(\omega)} \quad (4)$$

where $f_{xx}(\omega)$ and $f_{yy}(\omega)$ are the individual spectra of x_t and y_t . Although cross-correlation and cross-spectrum functions are used to analyze the correlation among random processes, they can also be used for the analysis of linear relations among deterministic variables, which is the case for the problem addressed here. More details about cross-correlation and cross-spectrum functions can be found in (Shumway and Stoffer 2005, Brillinger 2001).

For example, Figure 3.1-2 shows the performance of a rooftop unit located in a retail store in Texas. The plot shows 24 hr operation excluding unoccupied periods with a sampling rate of 1 min. The data were collected in the summer of 2008. The RTU has three cooling stages and three heating stages.

In Figure 3.1-3, the corresponding CHS, coherency, and phase functions are shown. The blue dash lines in the coherency and phase graphs are the confidence intervals. The flat line in the coherency graph shows the approximate value that must be exceeded by the squared coherency to confirm that the coherency is non-zero at the specified frequency ($\rho_{xy}^2(\omega) \neq 0$)⁴. Note that DAT and CHS are highly correlated at low frequencies. As there is usually a 2-3 minute delay between two consecutive heating/cooling commands, the CHS dominant frequencies are low-band (lower frequencies).

When there is a faulty stage of heating or cooling, the CHS/DAT correlation degrades. In order to isolate the faulty stage, the coherencies between DAT and a number of CHS's are compared. Each CHS is constructed based on the assumption that one or more cooling/heating stages is non-functional. When a stage is assumed to be non-functional, its associated $C_i(Q)$ or $H_i(Q)$ is set to zero. The CHS that has the strongest correlation with DAT is chosen as the closest match, and the corresponding assumption is concluded to be the operational status of the heating/cooling systems.

⁴ A second-order difference operator was applied to make the data stationary before calculating the coherency and phase.

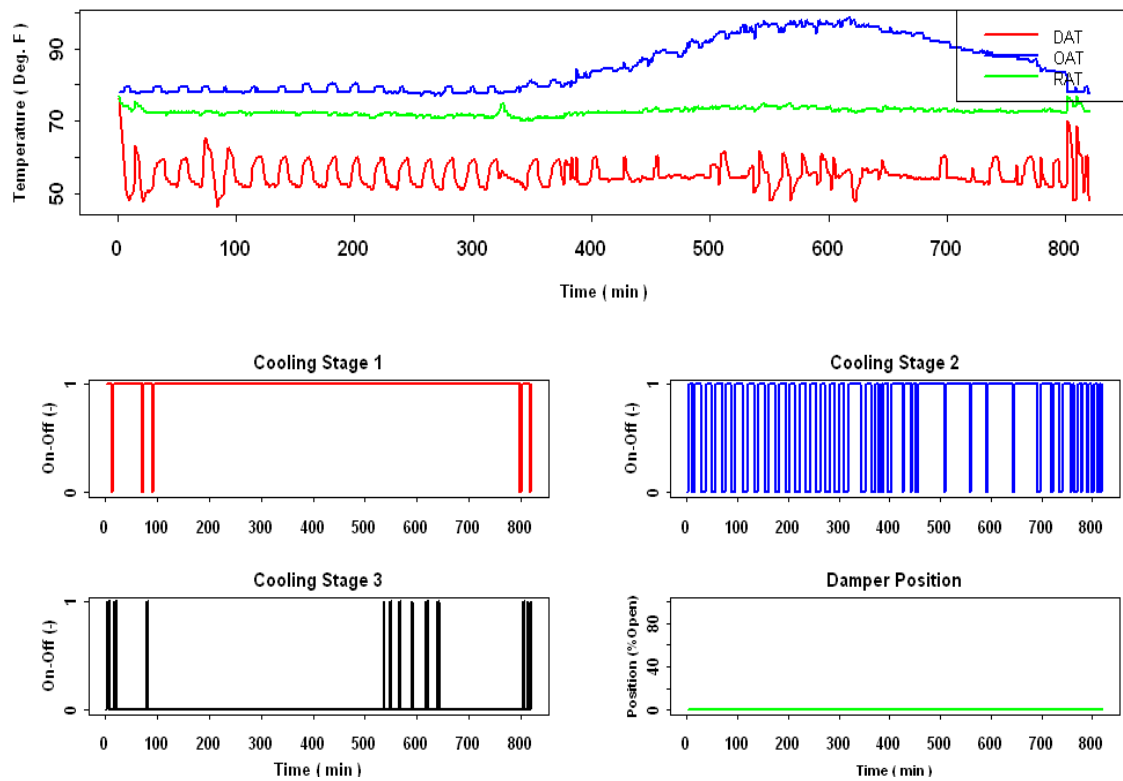


Figure 3.1-2: Performance of a rooftop unit performance located in a retail store in Texas

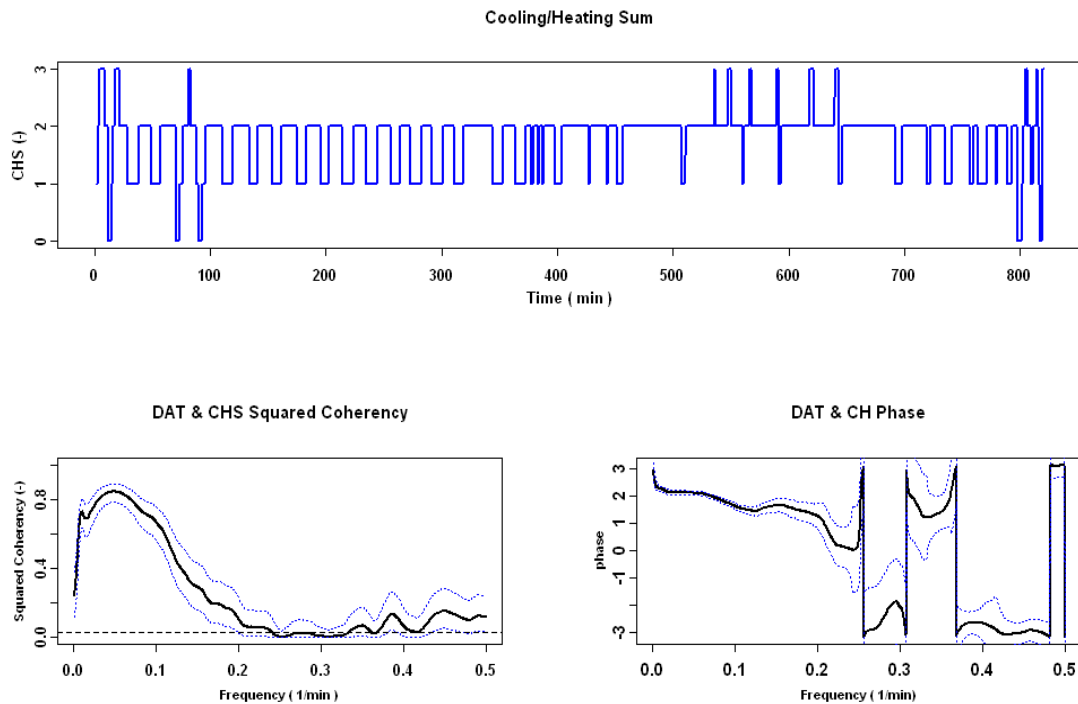


Figure 3.1-3: The cooling/heating sum (CHS), coherency, and phase between the DAT and CHS of the RTU in Figure 3.1-2

For example, in Figure 3.1-4, three different CHSs and the corresponding coherency graphs of the RTU in Figure 3.1-2 are shown.⁵ Note that the no-fault case has the highest correlation, as expected.

As another example, Figure 3.1-5 shows the performance of another RTU located in a different retail store in California. The data cover 24 hrs, excluding unoccupied periods, with a sampling rate of 1 min, and were collected in the summer of 2008. The RTU has three cooling stages and three heating stages. Visual inspection indicates that the DAT does not respond as the first stage of cooling is activated. This suggests that the cooling stage 1 might be faulty. In Figure 3.1-6, various CHS's and the corresponding coherency graphs are shown. It is clear that the case corresponding to a non-functional cooling stage 1 has the highest correlation.

⁵ A sample of all the scenarios is shown.

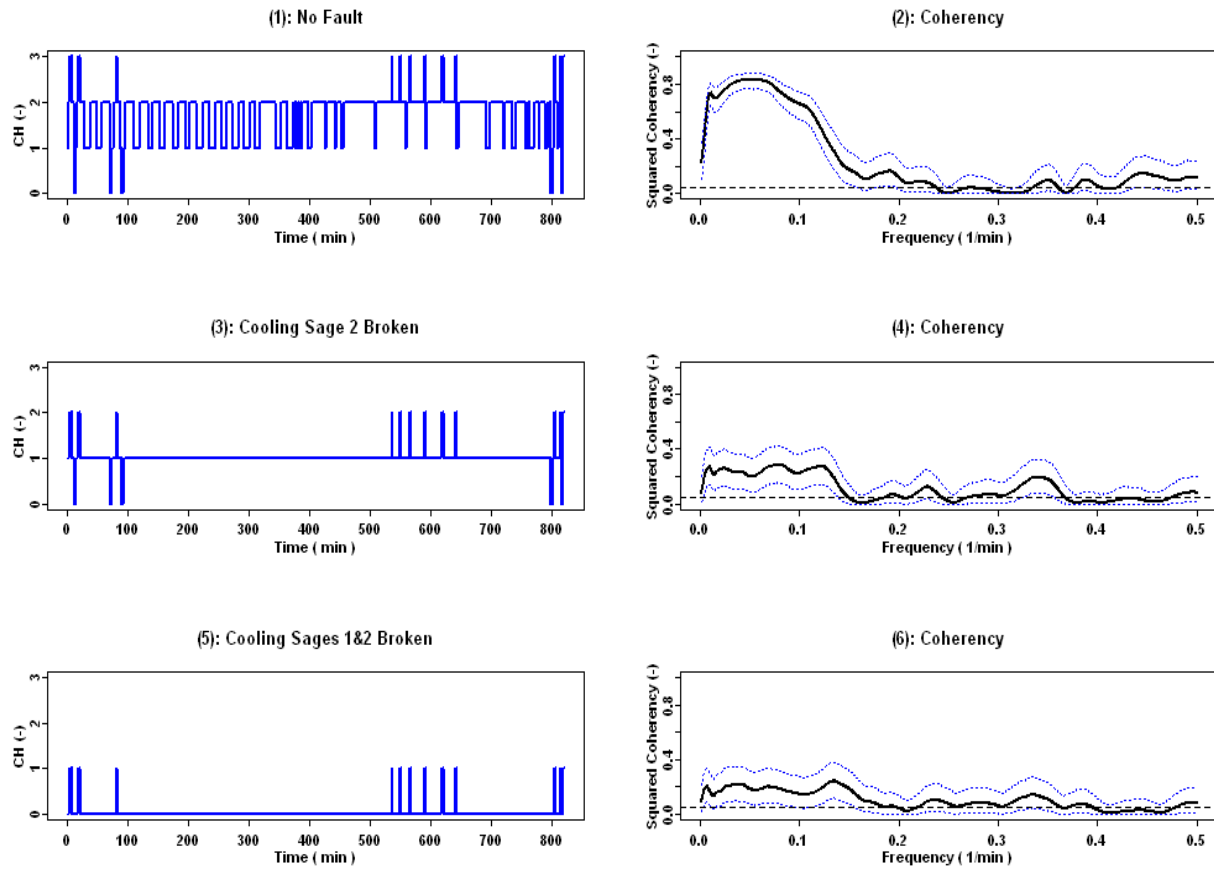


Figure 3.1-4: A number of CHSs and the corresponding coherencies based on different hypotheses for the RTU shown in Figure 3.1-2.

3.1.2. *Mixing box diagnostics*

Mixing box faults include actuator reverse action, damper leakage, and stuck dampers. As mentioned earlier, one challenge in mixing box diagnostics is to deal with the lack of a mixed air temperature measurement (Figure 3.1-1); the main measured variable that is directly affected by the mixing box functionality is the discharge air temperature, which is also affected by the coil behavior. The challenge is how to differentiate between coil effects and mixing box effects. One approach is to analyze mixing box performance while the coils are off. This may not be compatible with normal operation unless the system is in free cooling mode.

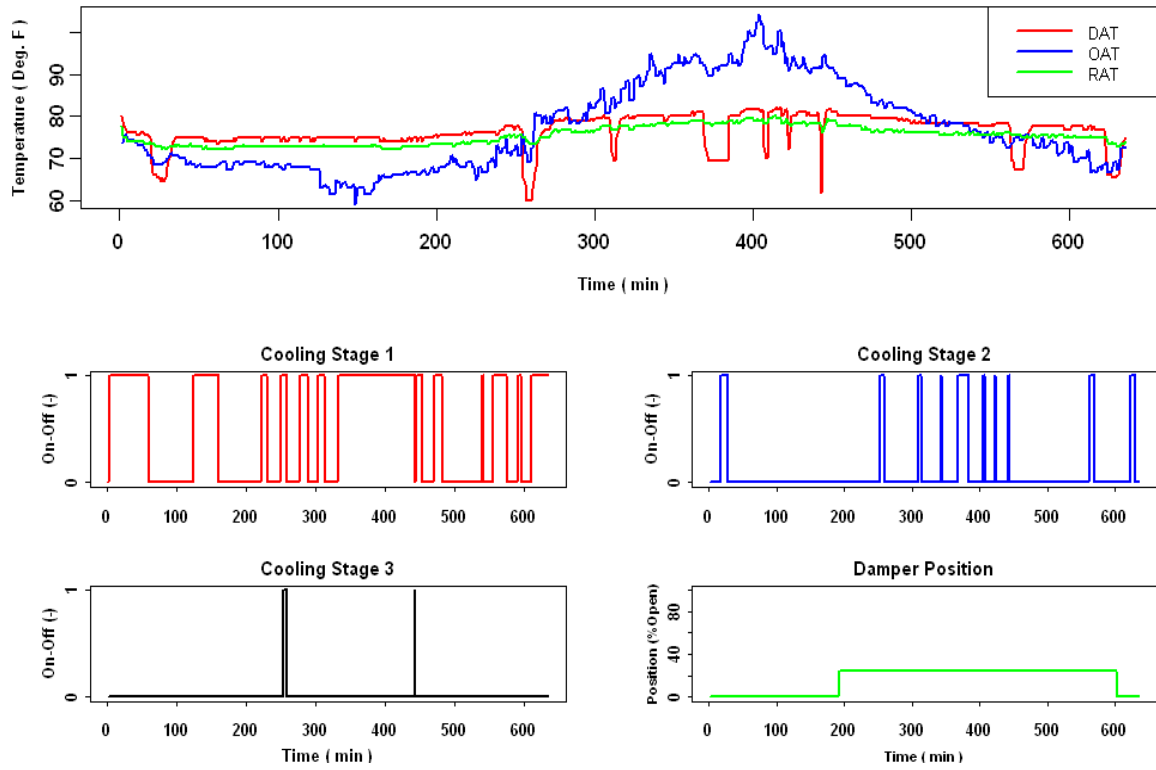


Figure 3.1-5: Rooftop unit performance located in a retail store in California

The approach adopted is first to remove the coil effect from the DAT variations and then use the filtered DAT to analyze mixing box performance. The filtering coil effect can be achieved by finding θ_c , which minimizes the following mean squared error function:⁶

⁶Here, we again assume a linear relation between heating/cooling command and DAT variations.

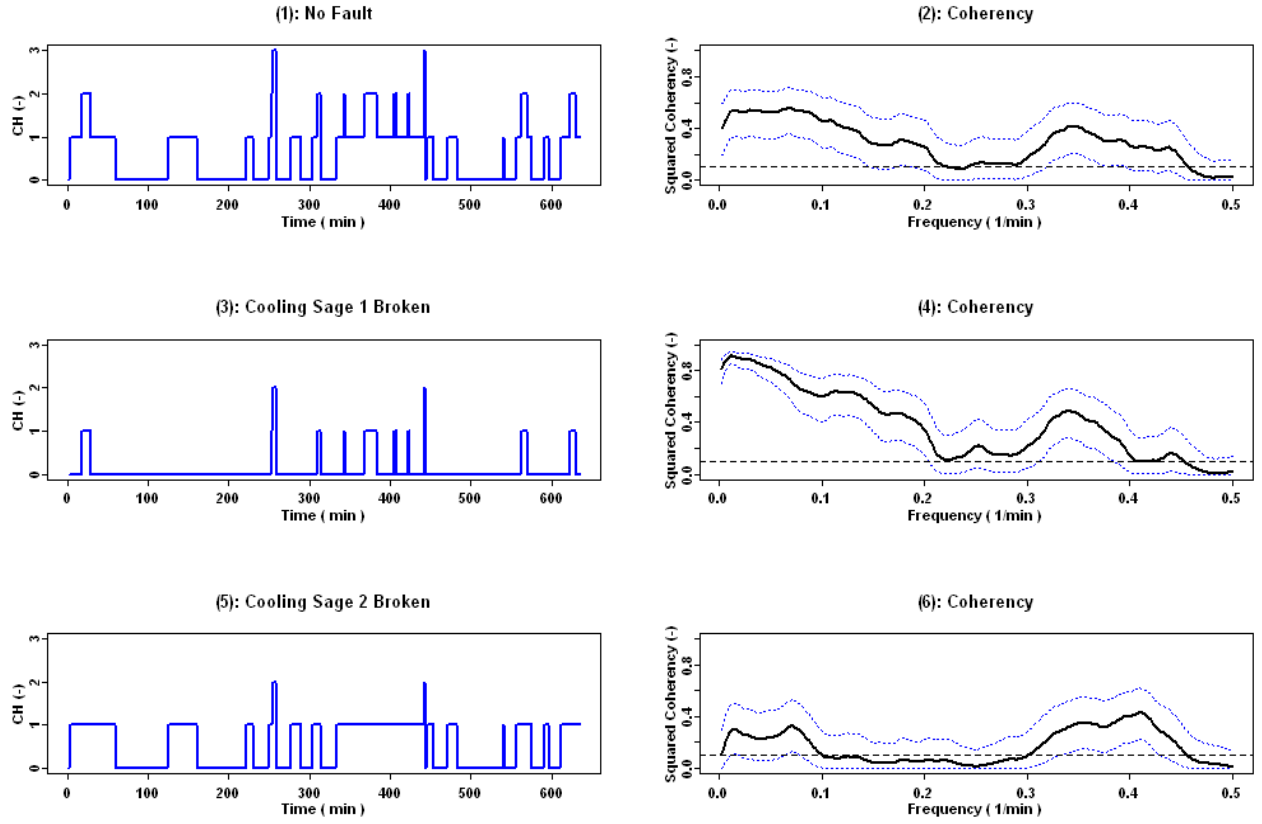


Figure 3.1-6: A number of CHSs and the corresponding coherencies based on various hypotheses for the RTU shown in Figure 3.1-5

$$MSE = E \left(DAT_t - \sum_{r=-\infty}^{\infty} \beta_r CHS_{t-r} \right)^2 \quad (5)$$

The Fourier transform of $\{ \beta_r \}$ can be estimated as [20]:

$$\hat{\beta}(\omega_k) = \frac{\hat{f}_{DAT \& CHS}(\omega_k)}{\hat{f}_{CHS \& CHS}(\omega_k)} \quad (6)$$

$\{ \beta_r \}$ can then be found by the inverse Fourier transform of $\hat{\beta}(\omega_k)$. The estimated β_r for the RTU in Figure 5 is shown in Figure 7. A possible model for β_r is:

$$\sum_{r=-\infty}^{\infty} \beta_r CHS_{t-r} = -1.1CHS_{t-1} - 1.43CHS_{t-2} - 0.98CHS_{t-3} - 3.12CHS_t + 1.29CHS_{t+1} + 0.70CHS_{t+2} + 0.86CHS_{t+3} \quad (7)$$

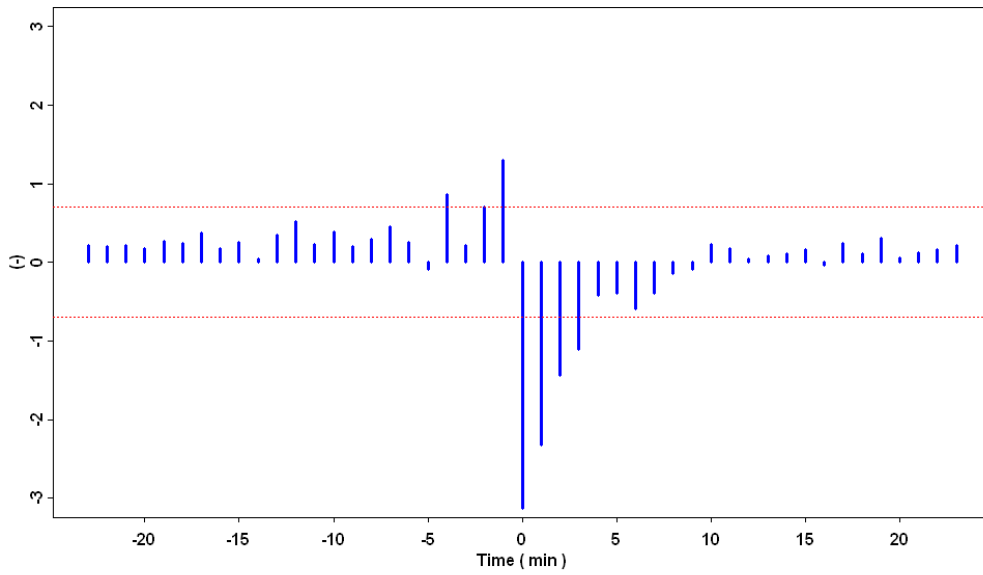


Figure 3.1-7: Estimated β_t for the data shown in Figure 3.1-5

Now, the filtered DAT, an estimation of MAT, is⁷:

$$MAT_t = DAT_t - \sum_{\tau=-\infty}^{\infty} \beta_{t-\tau} CHS_{t-\tau} \quad (8)$$

In the mixing box, the relation between MAT and OAT/RAT depends on the damper position. A simple mixing box model is:⁸

$$MAT = \left(\frac{DMP}{100}\right) \cdot OAT + \left(1 - \frac{DMP}{100}\right) \cdot RAT \quad (9)$$

⁷Note that, the value of the supply fan temperature rise should be included in Equation 8. However, in the constant-air-volume (CAV) systems typically used in retail stores, this temperature rise is constant and so its only effect is to decrease the coherency function at zero frequency. Since the fan temperature rise is typically small compared to the temperature change due to a single stage of heating or cooling, it has negligible effect on the determination of whether a particular stage of heating or cooling is operational.

⁸This is a very simplified model of the mixing box. In reality, the mixed air temperature depends on other factors such as the damper type, the configuration of the ductwork and the pressures of the return and mixed air, etc. However, most of these parameters are not easily measureable, so this simplified model has been employed.

Similar to the heating/cooling system scenario, the approach is to compare the correlation between the estimated MAT (filtered DAT) with a number of MAT correlations generated assuming the presence of one or more faults. The one with the strongest correlation is chosen as the best estimate of mixing box status (correct operation or specific fault).

As an example, using the filtered DAT from Equations 4 and 5, Figure 8 shows the coherency and phase functions for three scenarios (no fault, reverse actuator fault, and stuck damper fault). Note that the no-fault case has the highest correlation, meaning that the mixing box appears to be operating correctly. The correlations are weaker than those shown in Figures 4 and 5 because of the limited excitation of the damper position.

As another example, Figure 3.1-9 shows simulated performance of a rooftop unit with the stuck damper fault. Using the same diagnostic framework, Figure 3.1-10 shows that the stuck damper case has a higher correlation than the other cases.

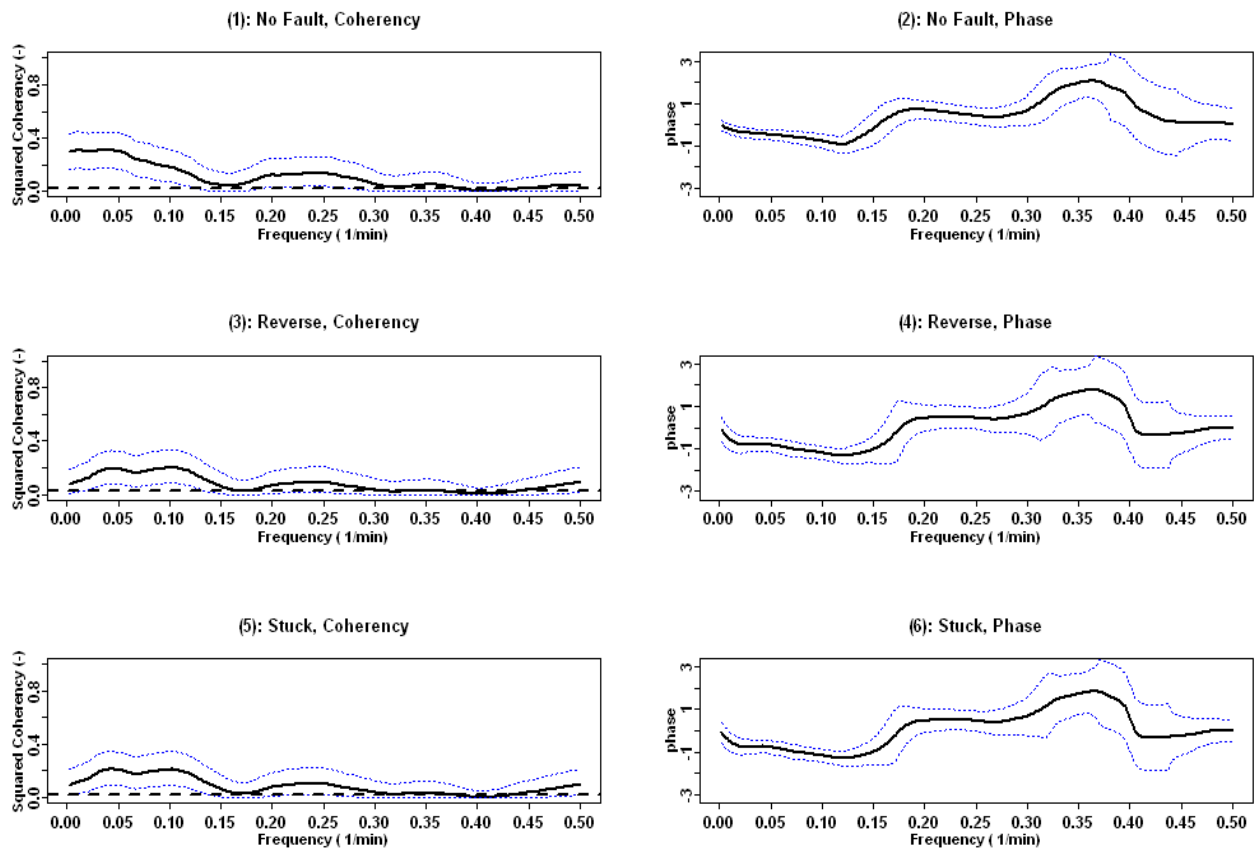


Figure 3.1-8: The coherency and phase functions for three different scenarios (no fault, reverse actuator, and stuck damper) for the RTU in Figure 3.1-5

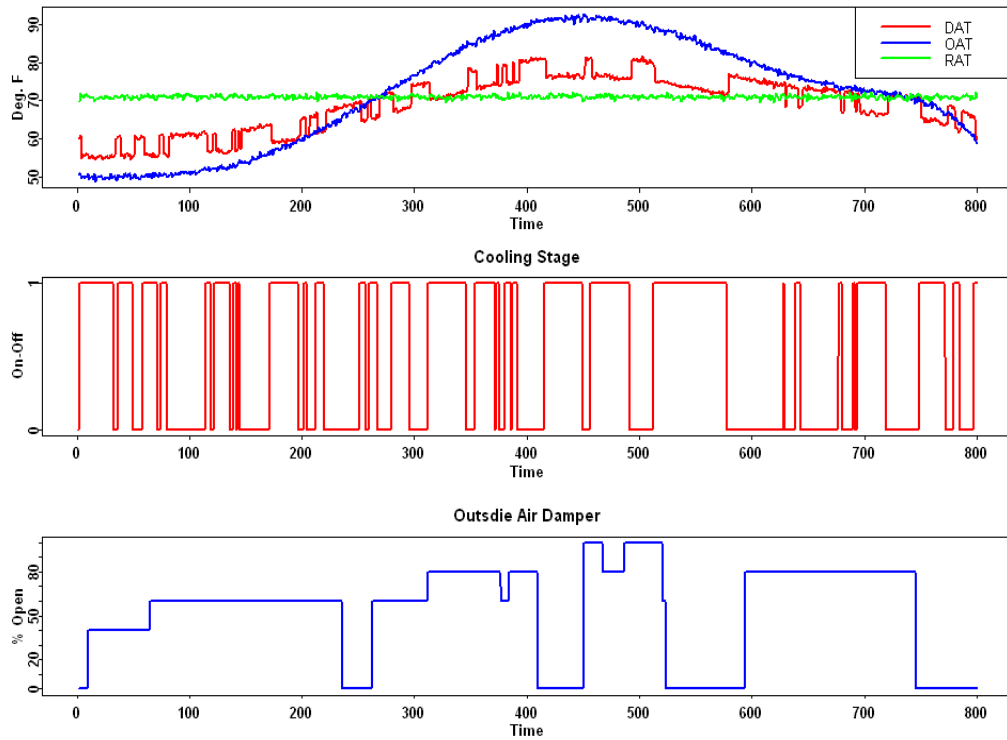


Figure 3.1-9: Simulated performance of a rooftop unit with stuck damper fault. The damper position has been manipulated deliberately to generate sufficient excitation

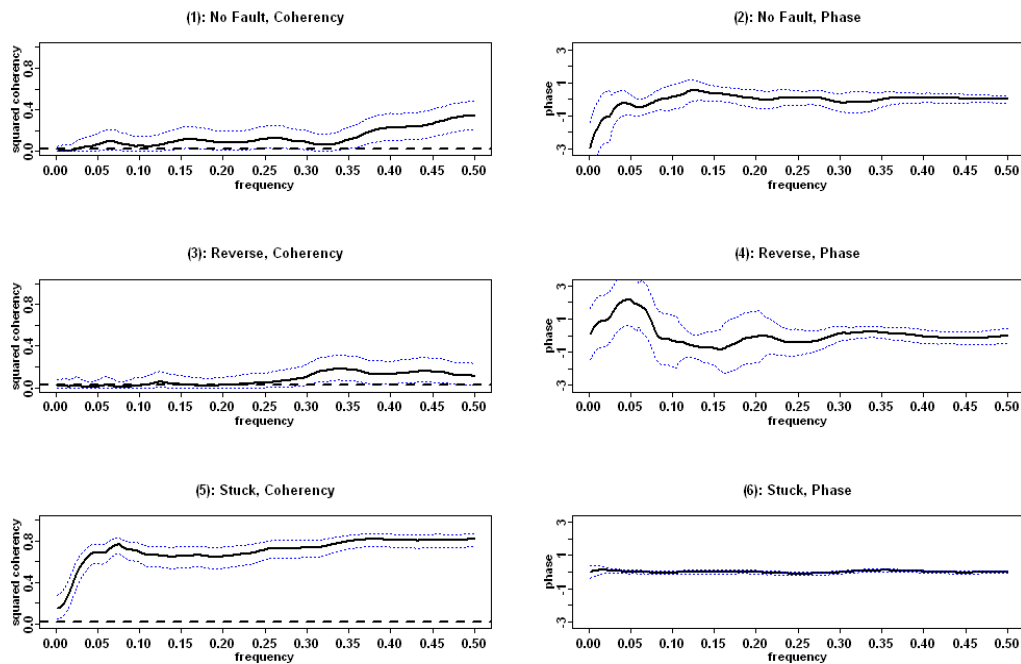


Figure 3.1-10: The coherency and phase functions for three different scenarios (no fault, reverse actuator, and stuck damper) for the RTU in Figure 3.1-9

3.2. Project Outcomes for Adding Energy to Learn HVAC

The major project outcome for Learn HVAC has been adding important energy analysis capabilities to the educational software tool Learn HVAC 1.0. The results of this project will allow students to understand the principles underlying both the design and operation of efficient systems and to diagnose the causes of inefficient operation

The new Learn HVAC 2.0 version includes a number of enhancements and refinements to Learn HVAC 1.0 including:

- New energy and peak demand analysis capabilities
- Integrated EnergyPlus⁹ energy simulations with
 - Selected easy-to-use inputs to EnergyPlus
 - A macro-driven EnergyPlus prototypical office building
 - Selected graphical outputs from EnergyPlus
 - The ability to include two EnergyPlus simulations within any scenario
- New heating and cooling plant components (boiler, chiller, cooling tower)
- Refined SPARK¹⁰ component simulation models with documentation of model operation.
- Refinements to the control structure used for the HVAC system
- Refinements to several Learn HVAC user interface features

Two example screens from the Learn HVAC 2.0 version are shown below in Figure 3.2-1. These screens are from the Alpha version of Learn HVAC 2.0 that is being produced by this project.

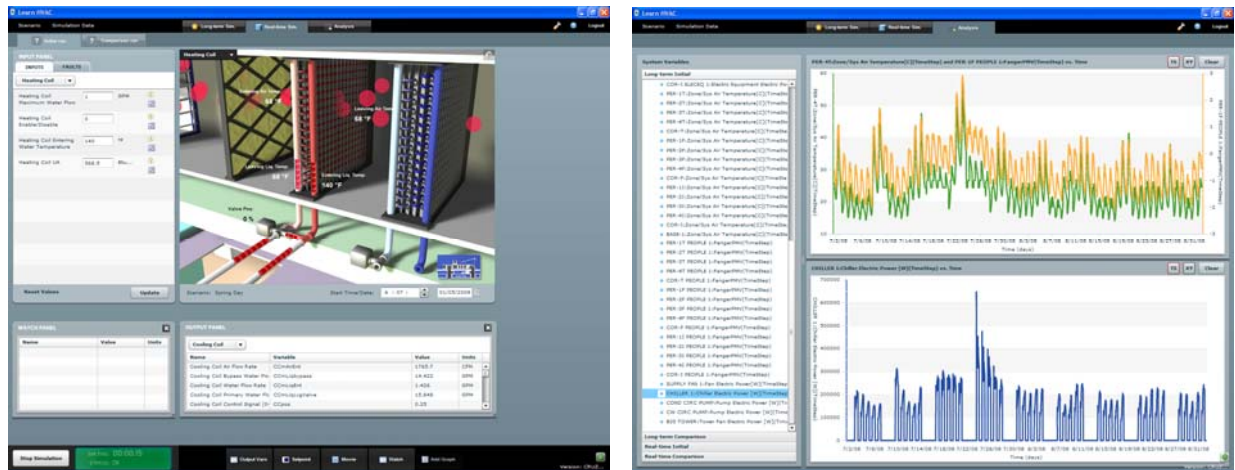
3.2.1. **Add Energy and Peak Demand Analysis Capabilities**

Learn HVAC 1.0, available in mid-2007 at the beginning of this Energy Commission project, contained detailed component-level equipment models for simulating a typical air-handling unit for short time spans using very short time steps, typically one second. However, it did not include any capabilities for estimating longer-term energy and peak demand impacts of short-term HVAC operations. This was considered a major shortcoming.

⁹ <http://www.energyplus.gov>

¹⁰ SPARK is an equation-based system simulation tool

Figure 3.2-1: New User interface features of Learn HVAC 2.0



To properly address energy issues, this project added energy calculations to Learn HVAC. Such energy calculations typically involve much larger time spans (e.g., diurnal, monthly, and yearly) and longer time steps (e.g. hourly) than the second-by-second SPARK models used in Learn HVAC 1.0. The project team collaborated in devising mechanisms to handle both large and small time intervals and durations within the software, as part of the pedagogical objectives, the teaching analyses, and the scenarios.

The project team modified and extended the SPARK models and sets of variables for the typical air-handling unit that existed in mid-2007 so that they could accept basic inputs and provide basic outputs needed to address selected diurnal, monthly and annual energy and peak demand assessments, and to assess longer-term operations and time-intervals as well as the current short one second intervals.

3.2.2. *Integrate EnergyPlus into Learn HVAC*

Learn HVAC 1.0 had a single short term, real time, second-by-second simulation time scale. The new version, Learn HVAC 2.0, being produced by this Energy Commission project has added a second, long term time scale that enables users to see the long term (annual, monthly, diurnal) energy and operational consequences of their short term, real time decisions.

Thus, the user can now interact with each of two time scales:

1. An accurate, second-by-second simulation of a generic HVAC system and the dynamics of its controls. The system is coupled to a series of 3D animations that present its performance in a visually realistic way.
2. Long term annual, monthly, or diurnal EnergyPlus simulations that compare energy and load impacts of the short term HVAC system conditions.

Figure 3.2-2 below shows the tabs at the top of the screen that allows a user to choose between the short-term, real time simulations and the long term, EnergyPlus-based simulations.

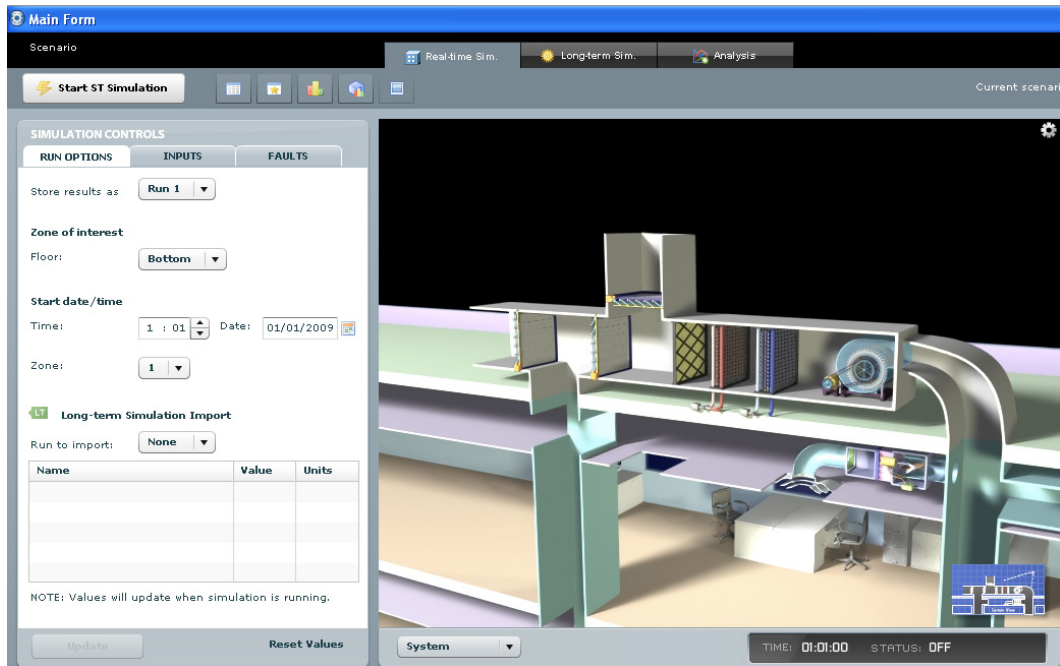


Figure 3.2-2: Learn HVAC main menu produced by this Energy Commission Project

The integration of EnergyPlus into Learn HVAC 2.0 includes the use of a large office prototype in order to help simplify the application of EnergyPlus within this educational software environment. The large office prototype contains a number of macros that permit key building features to be easily modified. This includes such features as:

- Building length and width
- Number of stories
- Floor-to-floor height
- Window-to-wall ratio for each of 4 orientations
- Type of window – strip or punched.
- Lighting level (w/sf, same for all zones)
- Equipment level (w/sf, same for all zones)
- Square foot per person

The project team has added several selected variables to the system variables used in Learn HVAC 2.0 to permit a proof-of-concept demonstration of modifying EnergyPlus prototype building input descriptions from within the Learn HVAC 2.0 program as part of energy-related scenarios. These proof-of-concept features will permit, when developed further in the future, such prototypes to become part of standard teaching scenarios, and will greatly increase the flexibility and range of such scenarios.

As part of this outcome, extensions to the existing Flash Graphical User Interface (GUI) were developed to provide links, input displays, and output displays to permit EnergyPlus analyses to be initiated from within Learn HVAC 2.0, and to permit the display of selected summary EnergyPlus output results within the Learn HVAC Graphical User Interface (GUI) structure.

3.2.3. **Long Term Run Options for EnergyPlus**

The current interface allows for two EnergyPlus runs, each with its set of Run Options, as shown below in Figure 3.2-3. The Run Options tab allows a user to choose:

- The climate region and city, which will in turn select the climate file for the simulation. Shown in the example is the Northeast region and the city of Baltimore.
- The run period for the simulation. Shown in the example is a simulation of the month of January.

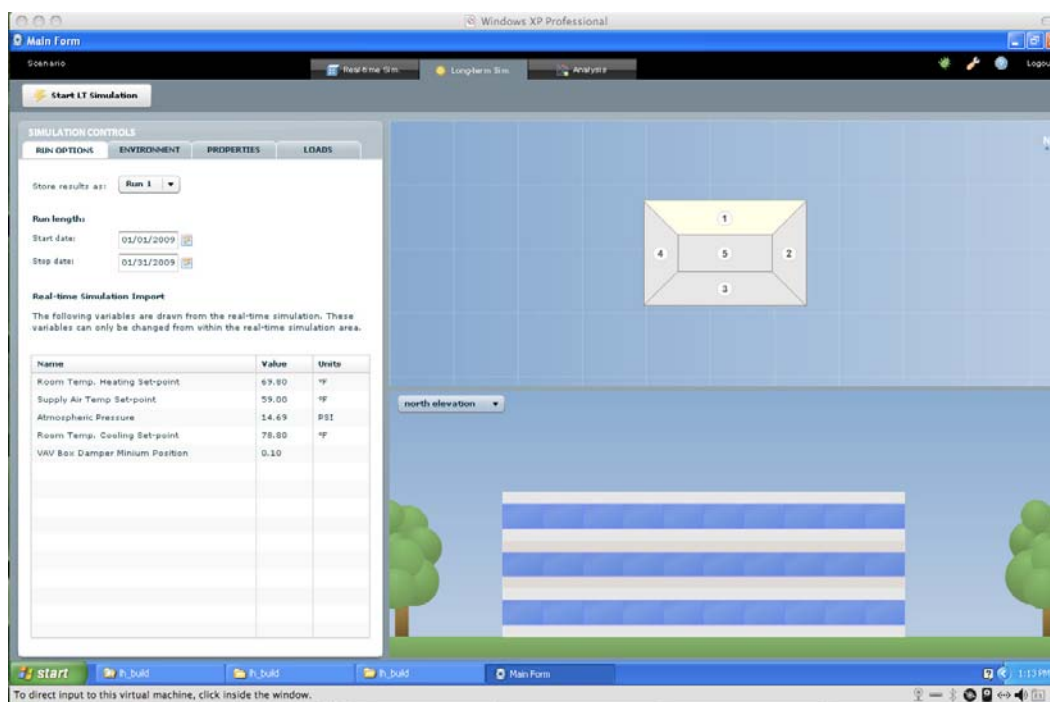


Figure 3.2-3; Run options for a Long Term EnergyPlus Run 1

3.2.4. **Building Properties for EnergyPlus**

The large office prototype contains a number of macros that permit key building features to be easily modified. As shown in Figure 3.2-4, this includes such features as:

- Building length and width
- Number of stories
- Floor-to-floor height

- Window-to-wall ratio for each of 4 orientations
- Type of window – strip or punched.

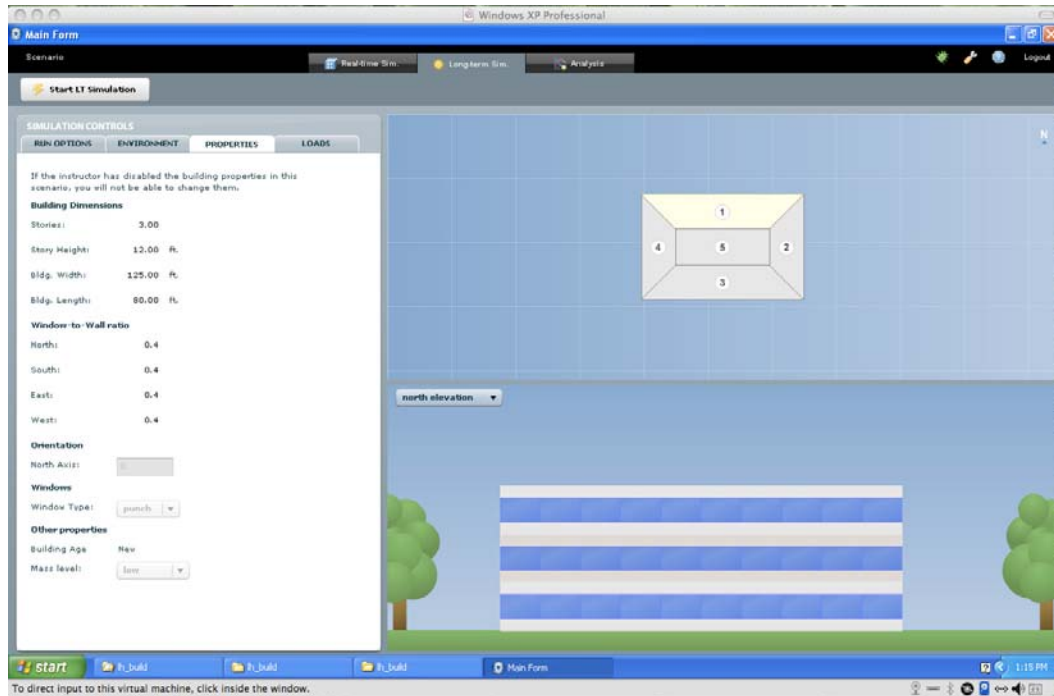


Figure 3.2-4: Building Properties for EnergyPlus Run 1

3.2.5. Internal Loads for EnergyPlus.

The large office prototype contains standard default values for key internal loads that are applied to all 15 zones in the prototype. These are shown in Figure 3.2-5 below and include:

- Lighting level (w/sf, same for all zones)
- Equipment level (w/sf, same for all zones)
- Square foot per person

The instructor can change these inputs for each scenario, and can lock the values for a scenario so that students cannot change the values for that scenario. If the values are not locked for a scenario, then the user (student, etc.) can use the Loads tab shown below to modify the input values for the internal loads that are used in the current EnergyPlus run.

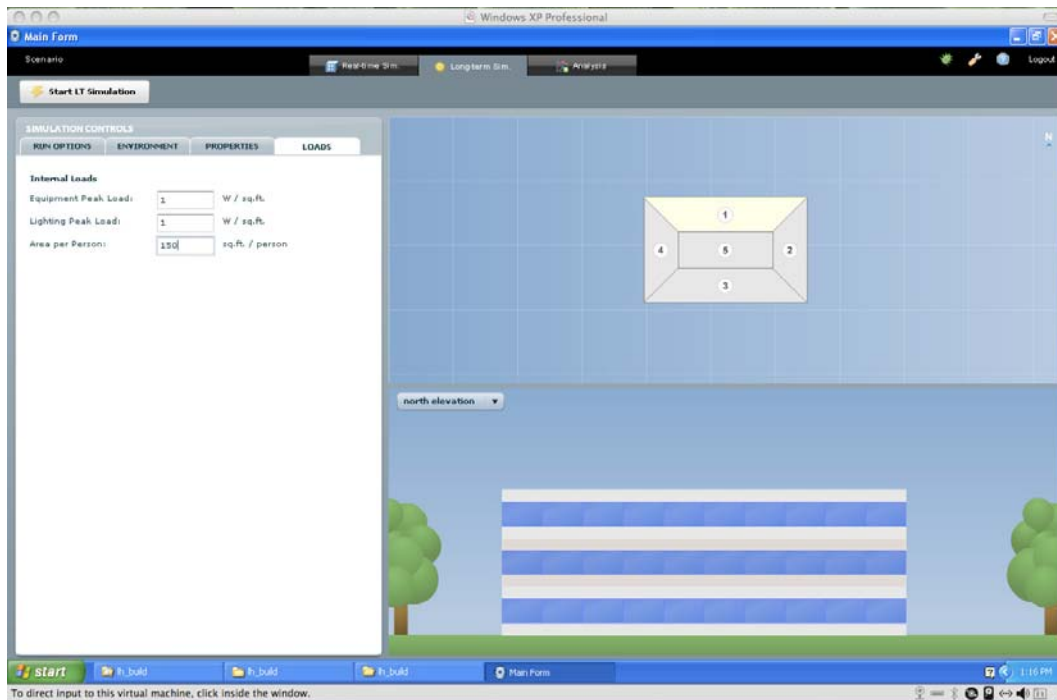


Figure 3.2-5: Building Properties for EnergyPlus Run 1

3.2.6. **Activating an EnergyPlus Run**

Once the run options, building properties, and internal loads have been selected to suit the current scenario, the user is ready to activate an EnergyPlus simulation run. This is done by clicking the white “Run LT Simulation” button in the upper left portion of the screen. Once the EnergyPlus simulation run begins, several changes occur to the GUI:

- The entire screen becomes slightly greyed out until the simulation run is completed. This can take several minutes
- A “Running EnergyPlus Simulation” dialog box appears in the center of the screen.
- An EnergyPlus button appears on the Status bar at the bottom of the screen that shows that the EnergyPlus program has been opened and is running.
- An EnergyPlus dialog box opens that shows the progress of activities in the batch file that controls the steps in the simulation.
- Lighting level (w/sf, same for all zones)
- Equipment level (w/sf, same for all zones)
- Square foot per person

The large office prototype contains standard default values for key internal loads that are applied to all 15 zones in the prototype. These include:

- Lighting level (w/sf, same for all zones)
- Equipment level (w/sf, same for all zones)
- Square foot per person

The instructor can change these inputs for each scenario, and can lock the values for a scenario so that students cannot change the values for that scenario. If the values are not locked for a scenario, then the user (student, etc.) can use the Loads tab shown below to modify the input values for the internal loads that are used in the current EnergyPlus run.

3.2.7. New heating and cooling plant components (boiler, chiller, cooling tower)

The project team added the component and system models required to simulate a chilled water plant with cooling towers to the set of SPARK models used within the HVAC ePrimer framework. These are basic steady state models without controls or faults.

As part of this outcome BCBP has developed basic 3D graphics models of the HVAC plant, including boiler, chiller, and cooling tower.

Example views of these new components in Learn HVAC 2.0 are shown in Figure 3.2-6.

The project team has linked these new 3D models into the overall Learn HVAC GUI, and has provided means for users to transition GUI attention among all system elements.

The project team has also provided extensions to the existing “System Variables” to address the SPARK input-output requirements for the new components.

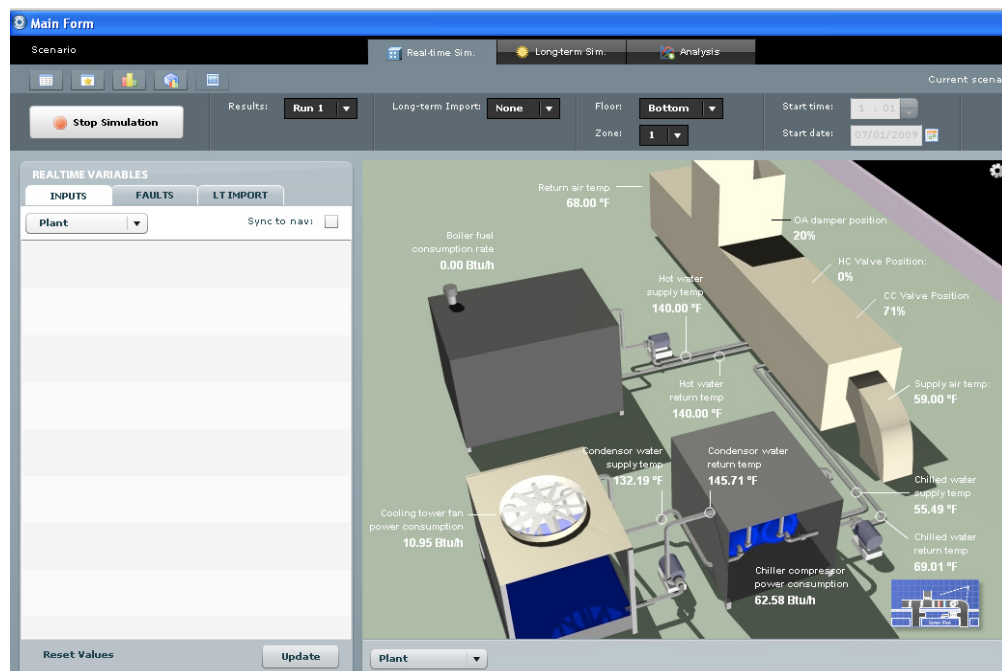


Figure 3.2-6a: View of HVAC plant

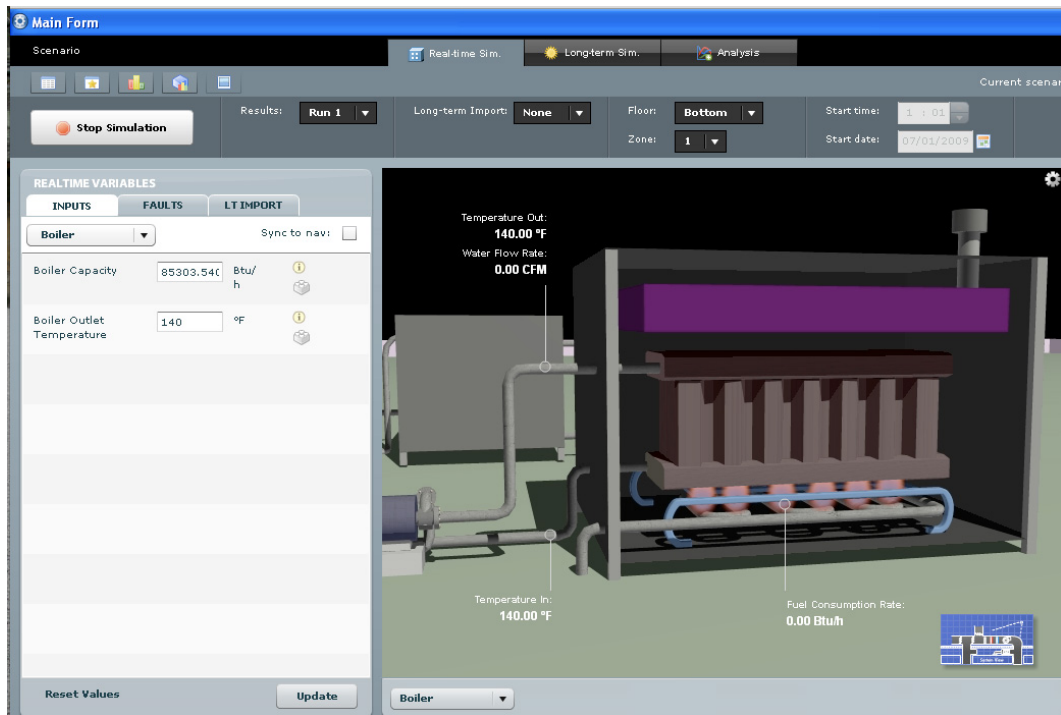


Figure 3.2-6b: View of Boiler

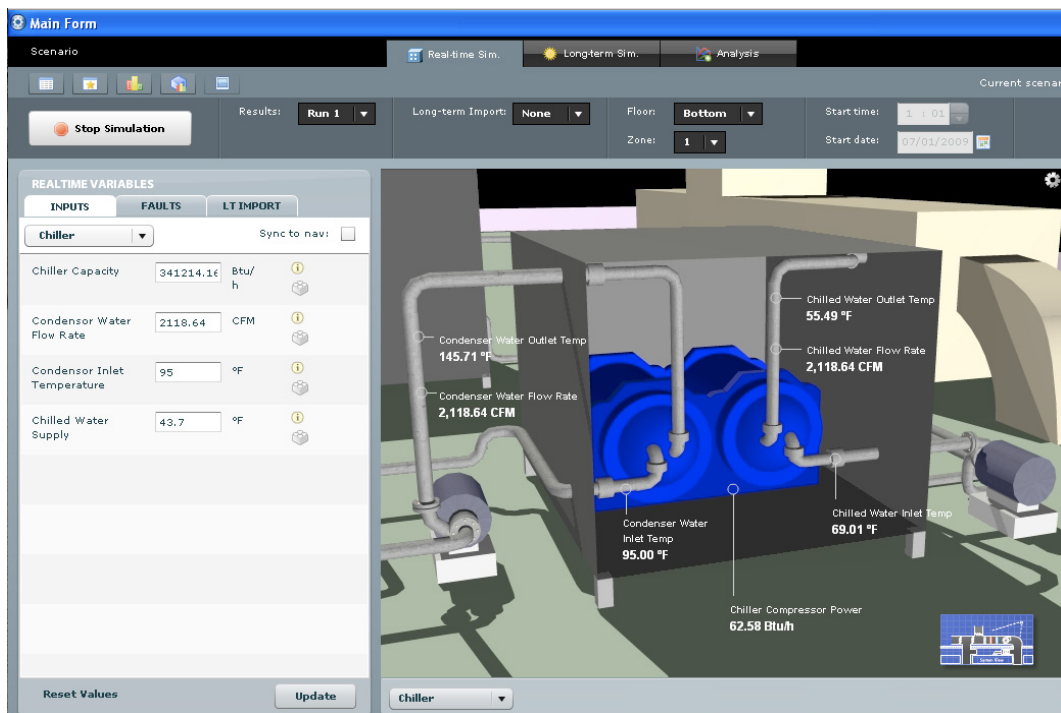


Figure 3.2-6c: View of Chiller

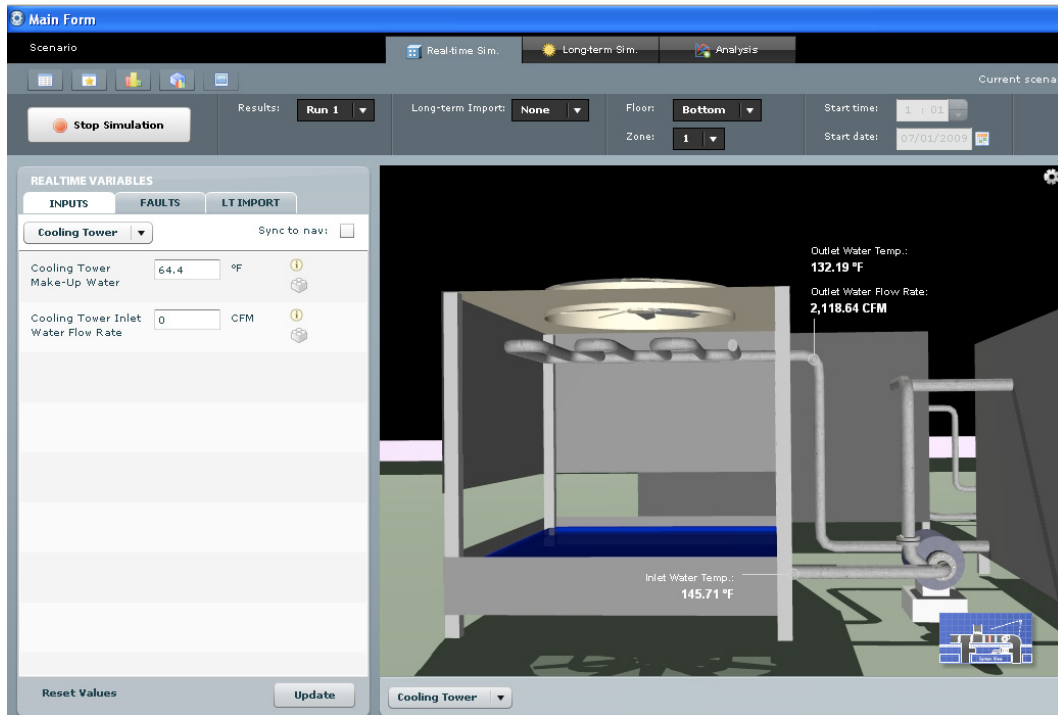


Figure 3.2-6d: View of Cooling Tower

3.2.8. *Refined HVAC Controls in Learn HVAC 2.0 alpha*

Control Loops: The control loops in Learn HVAC 1.0 had several shortcomings. To overcome these, during this project the controls loops were substantially revised in the SPARK models used in Learn HVAC 2.0 alpha.

The control of the HVAC system is split into two loops:

- One loop is controlling the room temperature by modulating the VAV-box damper and reheat coil; and
- The other loop is controlling the supply air temperature by controlling the mixing box, heating coil and cooling coil.

In the SPARK model, both loops are controlled by PI controllers. (As shown in Section 4, a PI model can be replaced by hardware controllers of any type.) Split range control is used for the mixing box, heating coil and cooling coil, as shown in Figure 3.2-7.

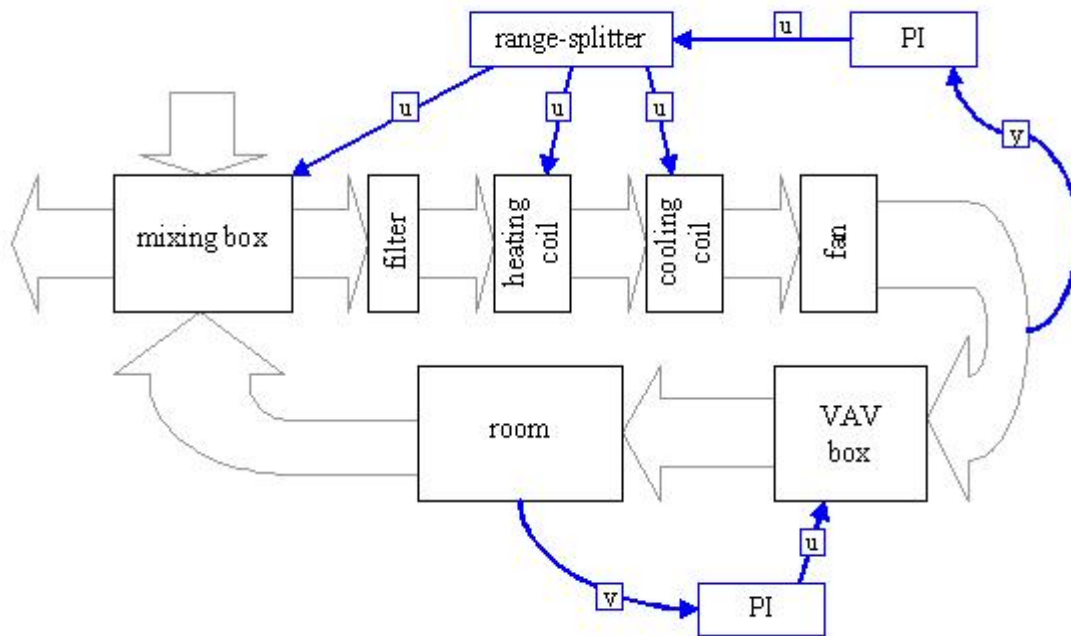


Figure 3.2-7: Control Structure

3.2.9. ***Project Outcome – Refine Learn HVAC User Interface Features***

The existing 2007 Flash-based Graphic User Interface (“GUI”) and related data handling capabilities of Learn HVAC 1.0 were also refined, modified and extended in order to:

1. Update the GUI to the newly published latest version of Flash, including Flex, in order to improve flexibility and increase execution speed. This has been very successfully accomplished. The new versions of the GUI developed under this CEC project have been developed using FLEX and the latest versions of Flash. This has enabled a marked improvement in software development productivity.
2. Refine the functionality of the GUI, that existed in mid-2007; and,
3. Add new functionality to allow a user to enter or modify key energy-related input variables and to view key energy related output variables.

4.0 Conclusions and Recommendations

4.1. Conclusions for FDD for Rooftop Units

A new method of monitoring the operation of the heating, cooling and economizer subsystems of rooftop air-conditioning units and detecting and, in the case of some types of fault, diagnosing a variety of fault conditions has been developed. Limited testing using measured time-series performance data from rooftop units on 'big box' retail stores indicates that the method can detect some major faults with essentially no configuration effort and no additional sensors and can do so when equipment is cycling rather than being in steady state. The faults that can be detected include failure of one or more stages of heating or compressor cooling and failure of the economizer to modulate in free cooling mode. The method has its limitations; for heating or compressor cooling, the method does not detect faults that affect all stages equally, such as loss of refrigerant charge or condenser fouling. The method is potentially complementary to existing FDD methods for rooftop units, though further work is required to clarify this issue.

4.2. Conclusions for *Adding Energy to Learn HVAC*

This project has successfully developed an alpha version of Learn HVAC 2.0, with the new and refined features described above in this report and also below in Appendix A. This software should be very helpful in allowing numerous members of the building industry in California to better understand how energy-efficient HVAC systems work and how to troubleshoot systems that are not working properly.

4.3. Commercialization Potential for *FDD for Rooftop Units*

The description of the method has been submitted for publication in ASHRAE's research journal, the *International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research*. The response to this paper will provide one indication of the commercialization interest. The method will also be discussed with members of DOE's Commercial Building Energy Alliance and with other researchers and stakeholders. The commercialization potential, if any, of the results of the FDD part of the project is not clear at this stage.

4.4. Commercialization Potential for *Adding Energy to Learn HVAC*

The pre-alpha version of Learn HVAC 1.0 has been available online since 2008, without advertisement. During this time several thousand people worldwide have downloaded the software. Very positive feedback has been provided.

From this experience we anticipate that more robust features of Learn HVAC 2.0 will permit its widespread use by numerous students, instructors, and interested persons. Its potential widespread use is enhanced because it is available for free and major elements are open source under Open Source License Version 3 (OSLv3).

The anticipated project results include a comprehensive interactive set of training tools for troubleshooting of several important commercial building energy-related systems and

components including HVAC, lighting, building envelope, and daylighting. The training is intended to transform the maintenance and operations of commercial building operations in the State of California. The project will make an immediate impact on the State of California by providing an alternative mechanism to train building technicians, operators, building managers, designers, contractors, and energy service providers to enhance building delivery and operations. The software has the potential to reach a much larger audience much faster than classroom training alone.

4.5. Recommendations for *FDD for Rooftop Units*

The original intent of the project was to develop rooftop FDD methods, and ways of implementing those methods, that are suitable for ‘big box’ retailers and others with networked, typically web-enabled, control systems. It is recommended that this general problem, and the method developed here, be discussed with the various stakeholders to determine the current relevance of, and interest in, the method developed here in the light of developments in the field that have occurred since the completion of the active research phase of the project reported here.

4.6. Recommendations for *Adding Energy to Learn HVAC*

It is recommended that additional funding be provided to:

- Complete Learn HVAC 2.0 beta, which will provide an adequate platform for widespread testing and preliminary use in the field throughout California as well as other locations in the country.
- Complete the final production version of Learn HVAC 2.0.
- Develop a more comprehensive Learn HVAC 3.0 version.

Learn HVAC 3.0 would include numerous new features, systems, and modules, and would address the needs of a much broader set of user types.

4.7. Benefits to California for *FDD for Rooftop Units*

Cooling by rooftop units accounts for a significant fraction of the electricity consumption and peak demand in California. In general, detection and correction of faults and operational problems results in improved efficiency, adequate capacity, or a combination of the two, resulting in reduced energy consumption, improved indoor environmental conditions, or both. The fault detection method developed in this project has the potential to make a contribution to the realization of these benefits for California.

4.8. Benefits to California for *Adding Energy to Learn HVAC*

Learn HVAC: Many HVAC systems in California do not provide the thermal comfort they were designed to provide, and they often use much more energy than intended. Improved understand of how HVAC systems should work will help California (1) improve the comfort conditions in its commercial building stock, thus improving productivity and (2) improve the

energy efficient operation of many HVAC system via improved understanding by building operators and O&M technical staff.

Commercial buildings in California consume ~67,000 GWh/yr of electricity and ~1,300 Mtherms/yr of natural gas.¹¹ Although there are no reliable data in California or the US on energy impacts associated with inefficient building development or operation, some estimates include:

- For new buildings, some 10 to 50 percent of potential energy efficiency is lost during project delivery from inadequate documentation and from knowledge-based problems that occur during design and construction (Vaidya, et al, 2008).
- For the operations of occupied buildings there is a general consensus that 10 to 30 percent of the energy is being wasted (Ardehali and Smith 2002, Claridge et al. 1996).

Thus, the following estimated savings from improved knowledge and skills of the workforce seem appropriate:

- 10 percent savings from improved delivery of new buildings and retrofit
- 10 percent savings from improved operation of buildings (less wasted).

Moreover, it is increasingly accepted that the biggest barrier to the achievement of the State's long-term building energy performance goals is the lack of a sufficiently skilled workforce¹². The #1 goal of the Workforce Education and Training element of the CPUC's Strategic Plan is to establish energy efficiency education and training at all levels of the state educational system. A specific example, cited in the Strategic Plan, of the actions needed to achieve the goals of the plan is to meet the need for supplementary training for existing stationary engineers (i.e. building operators) to enhance their awareness of energy efficient operations. This is part of the goal of this project. If the assessment is correct that worker training is inhibiting building efficiency improvement, Learn Green Lighting, Learn Green Envelope, Learn Daylighting, Learn HVAC, Learn Green Buildings and associated tools can play key roles in helping the State reach its energy goals.

There is currently a very high demand in the industry for technicians with good education and training, particularly controls technicians. Commissioning agents and design engineers with strong backgrounds in building energy performance are also in short supply, particularly in California. The development of Learn Green Lighting, together with the associated pedagogy, and its adoption in colleges, both in state and out of state, starting with the partner institutions in this project, can be expected to improve this situation in both the short term and long term.

¹¹ HVAC systems contribute approximately 28 percent of the entire electricity consumption and about 38 percent of the gas consumption in commercial buildings.

¹² California Long Term Energy Efficiency Strategic Plan at http://www.californiaenergyefficiency.com/docs/CA_longterm_EE_Strategic%20Plan.pdf

The training aspect in the five projects of our program is intended to transform commercial building maintenance and operations in the State of California. The five software development projects will together make an immediate impact to the State of California by providing an alternative mechanism to train building technicians, operators, building managers, designers, contractors, and energy service providers to enhance building delivery and operations. The software has the potential to reach a much larger audience much faster than classroom training alone.

The improved education and training from an advanced suite of educational software could substantially improve the distribution and depth of knowledge and skills in the workforce about energy efficiency and could thus help to transform both the delivery and the operations and maintenance of commercial buildings in the State of California.

The five software development projects will together make an immediate impact to the State of California by providing an alternative mechanism to train building technicians, operators, building managers, designers, contractors, and energy service providers to enhance building delivery and operations. The software has the potential to reach a much larger audience much faster than classroom training alone.

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Appendix A

This appendix describes details of three aspects of the new and refined HVAC system modules developed for inclusion in Learn HVAC 2.0 alpha as part of this project. The three aspects are:

- Details of the modeling of the various VAV system components, including views of 3D models of the components.
- Details of the new modules added to Learn HVAC 2.0 alpha as part of this project.
- Details of refinements to existing system modules that were accomplished as part of this project.

A.1 Details of the VAV System Component Modules

A.1.1 Mixing box and economizer

The return air from building spaces enters the mixing box, where some or all of it may be exhausted to the outside or returned to the supply air stream. The return air stream may be mixed with outside air.

The mixing box model selects damper positions that will vary the mix of return air (RA) and outside air (OA) to produce a mixed air temperature (MAT) close to the desired supply air temperature (SAT).

A minimum outside air (OA) fraction is included as a parameter to the model. The current outside air fraction is controlled by a minimum 20 percent outside air damper setting. Note that a damper setting of 20 percent does not necessarily mean that the resulting percentage of outside air is also 20 percent.

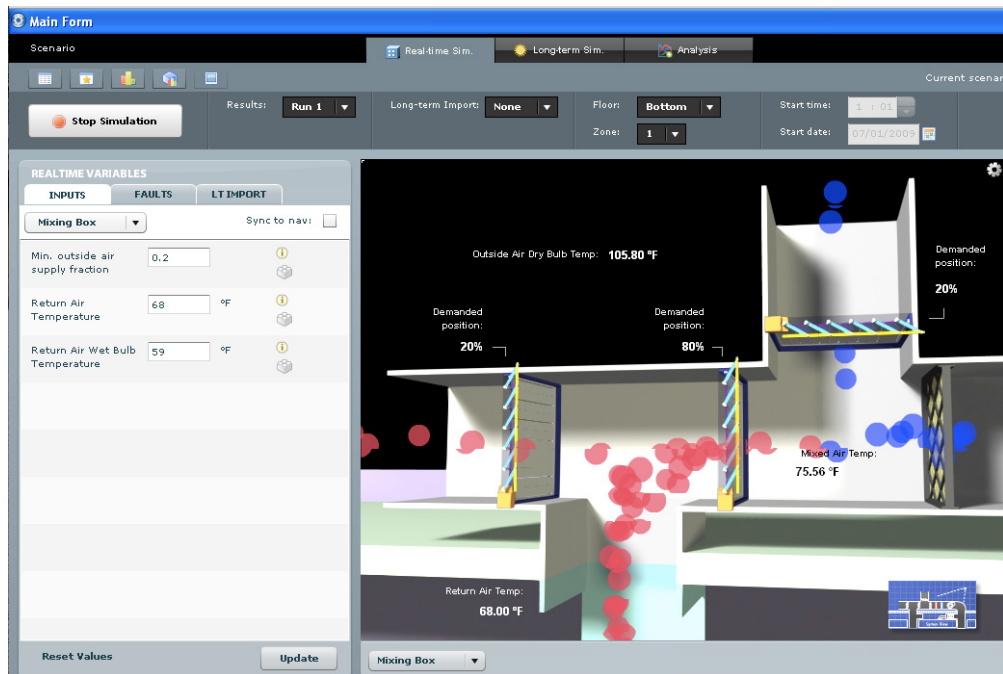


Figure A.1-1: View of mixing box on hot summer afternoon in Phoenix

A.1.2 Filter

Figure A.1-2 shows the view that the user sees of the filter, which is downstream from the mixing box and upstream from the heating coil.

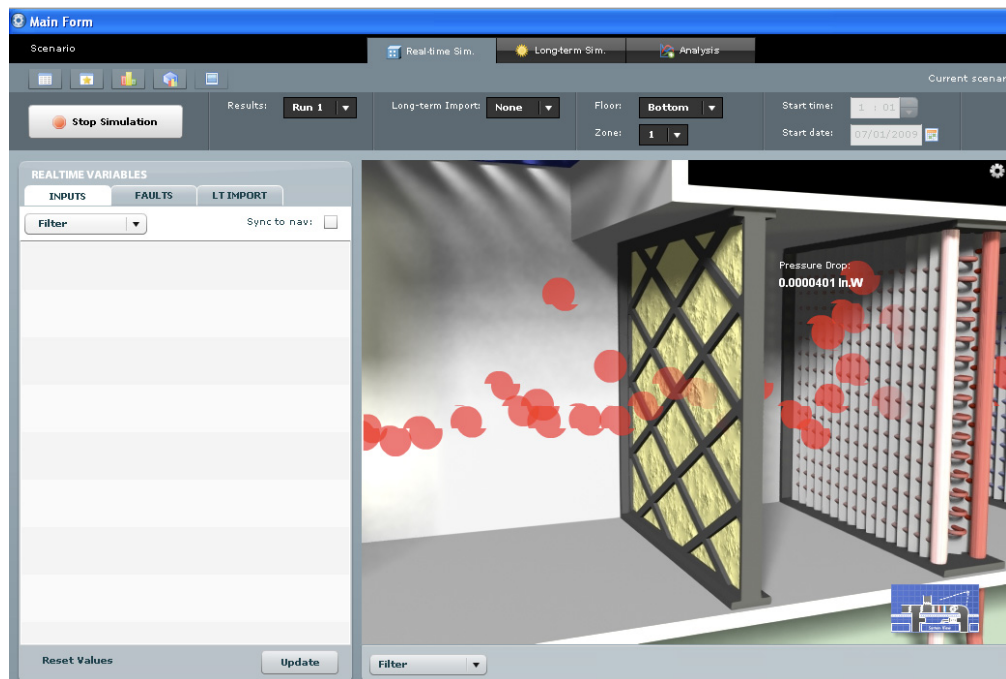


Figure A.1-2: View of filter

The filter model currently only performs a simple calculation of the pressure drop across the filter.

$$\text{filterPressureDrop} = c * \text{massFlowRate}^2 \quad (\text{Eq. A.2.1})$$

where c is an empirical constant, set to 0.01 within the model code.

Note that this model is essentially acting as a placeholder at present, since the pressure drops throughout the system are not being calculated explicitly.

A.1.3 Heating coil

Figure A.1-3 shows the view that the user sees of the heating coil, which is downstream from the mixing box and upstream from the heating coil.

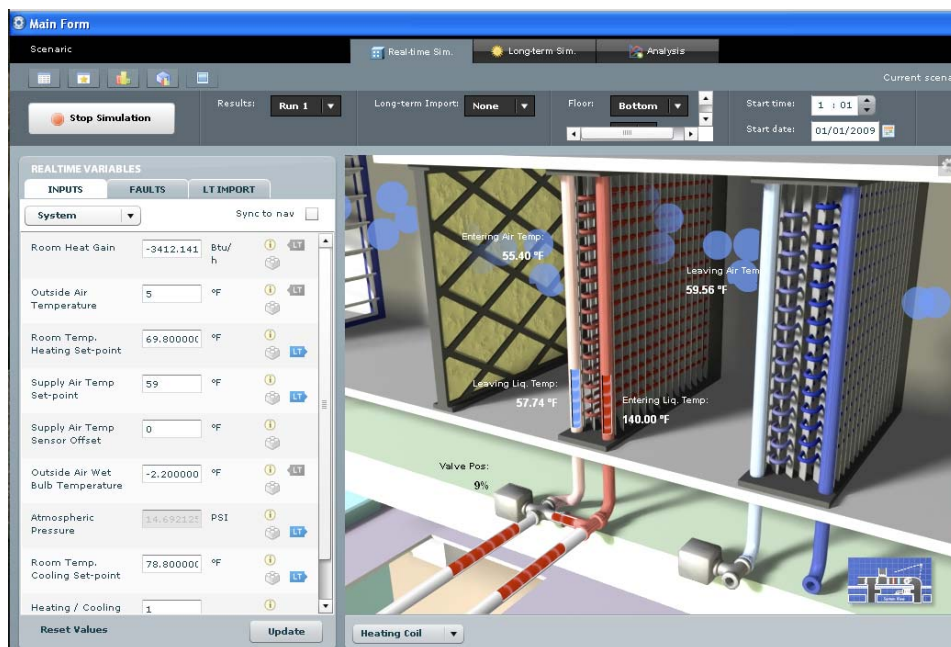


Figure A.1-3: View of heating coil

For a given scenario, the heating coil can be either “on” or “off.” If it is “off” then it is not available to provide heat, even though providing such heat may be desirable. If it is “on,” or active, then it is available to provide heat when called for. The action of an active heating coil is controlled by the desired temperature that has been specified for the supply air, 59°F, say. If the temperature of the air entering the heating coil is less than the specified 59°F supply air temperature (SAT), then the heating coil valve will open in order to allow some hot water from the boiler to pass through the heating coils, which will transfer heat to the air passing across the coils.

If the heating coil valve is completely closed, then all hot water from the boiler will bypass the heating coil via a “bypass” pipe at the valve.

The user is able to click on the image of heating coil valve on the screen and a 2-D popup will appear that displays details of hot water flows and temperatures, given the current status of the heating coil valve. An example of this is shown below in Figure A.1-4.

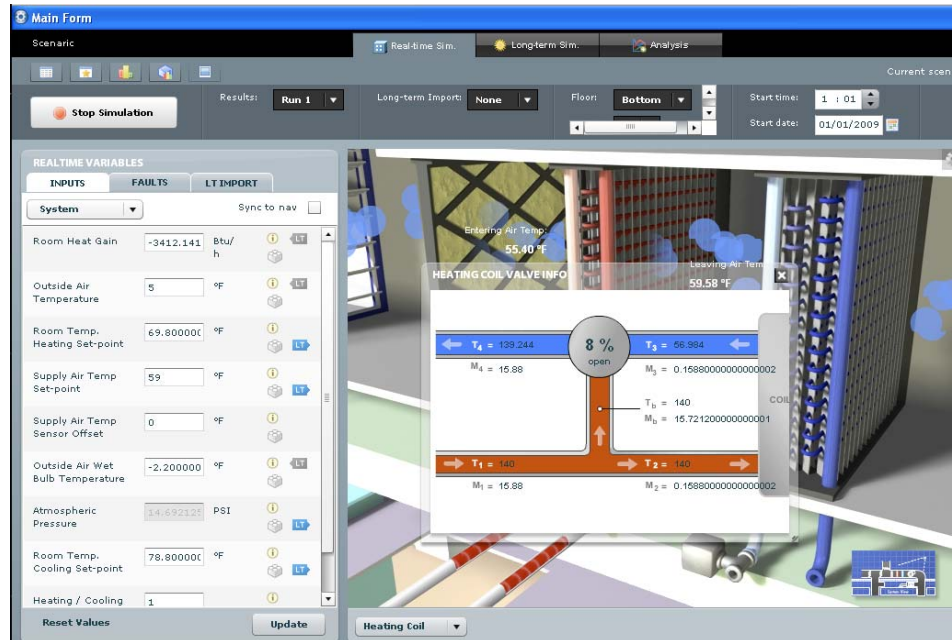


Figure A.1-4: View of popup view of heating coil valve

The heating coil examples shown above are for a cold winter morning where the outside air is only 5°F. The mixing box mixes 70 percent return air at 59°F with 20 percent outside air to produce a mixed air temperature of 54.4°F. The heating coil then heats this air to approximately the 59°F specified for the supply air. Note that this is still lower than the desired temperature of about 70°F in the occupied space.

However, the heating coil is the first of two locations in this HVAC system where the income air may be heated. There is also a reheat coil in the VAV box that is in the air stream for each zone prior to the supply air entering the space. The reheat coil in the VAV box is controlled by the air temperature in that space. See the description for the VAV box reheat coil below.

A.1.4 Cooling coil

Figure A.1-5 shows the view that the user sees of the cooling coil, which is downstream from the heating coil and upstream from the fan.

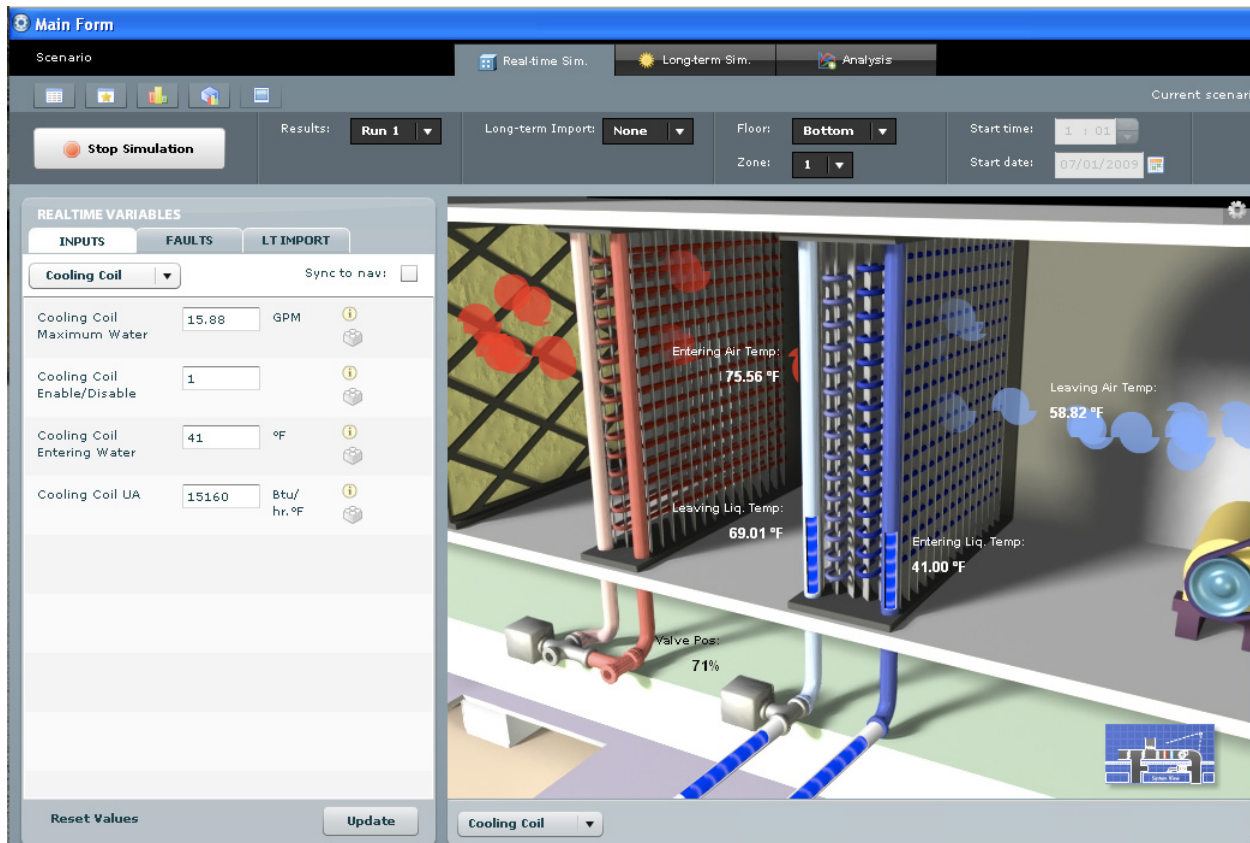


Figure A.1-5: View of cooling coil

For a given scenario, like the heating coil, the cooling coil can be either specified as “on” or “off.” If it is “off” then it is not available to provide cooling, even though providing such cooling may be desirable. If it is “on,” or active, then it is available to provide cooling when called for. The action of an active cooling coil is controlled by the desired temperature that has been specified for the supply air (i.e., 59°F). If the temperature of the air entering the cooling coil is greater than the specified 59°F supply air temperature (SAT), then the cooling coil valve will open up in order to allow some cold water from the chiller to pass through the cooling coils, which will extract heat from the air passing across the coils.

If the cooling coil valve is completely closed then no cold water from the chiller will pass through to the cooling coil.

The user is able to click on the image of cooling coil valve on the screen and a 2D popup will appear that displays details of water flows and temperatures, given the current status of the cooling coil valve.

A.1.5 Fan

Figure A.1-6 shows the view that the user sees of the fan, which is downstream from the cooling coil and upstream from the VAV box.

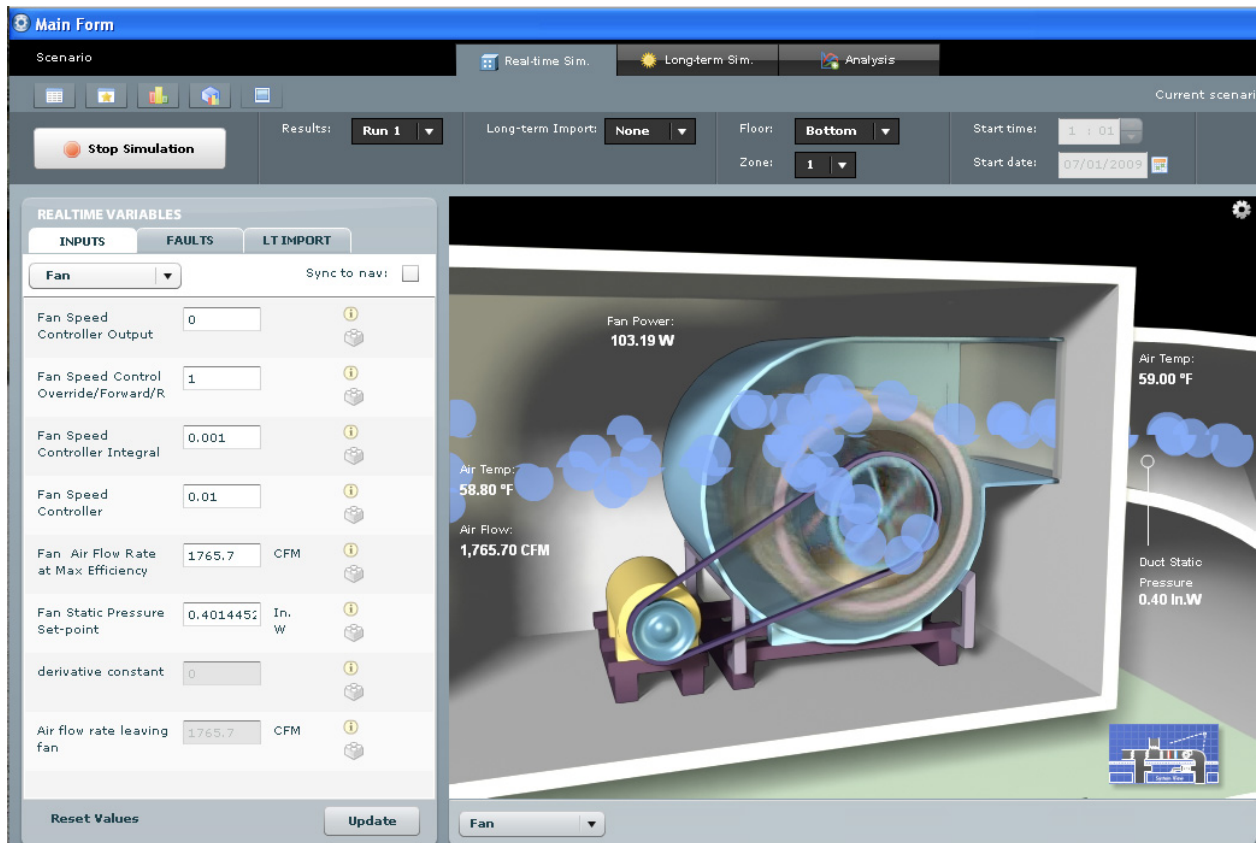


Figure A.1-6 View of fan

A.1.6 VAV box with reheat

Figure A.1-7 shows the view that the user sees of the VAV box, which is downstream from the fan and upstream from the diffuser.

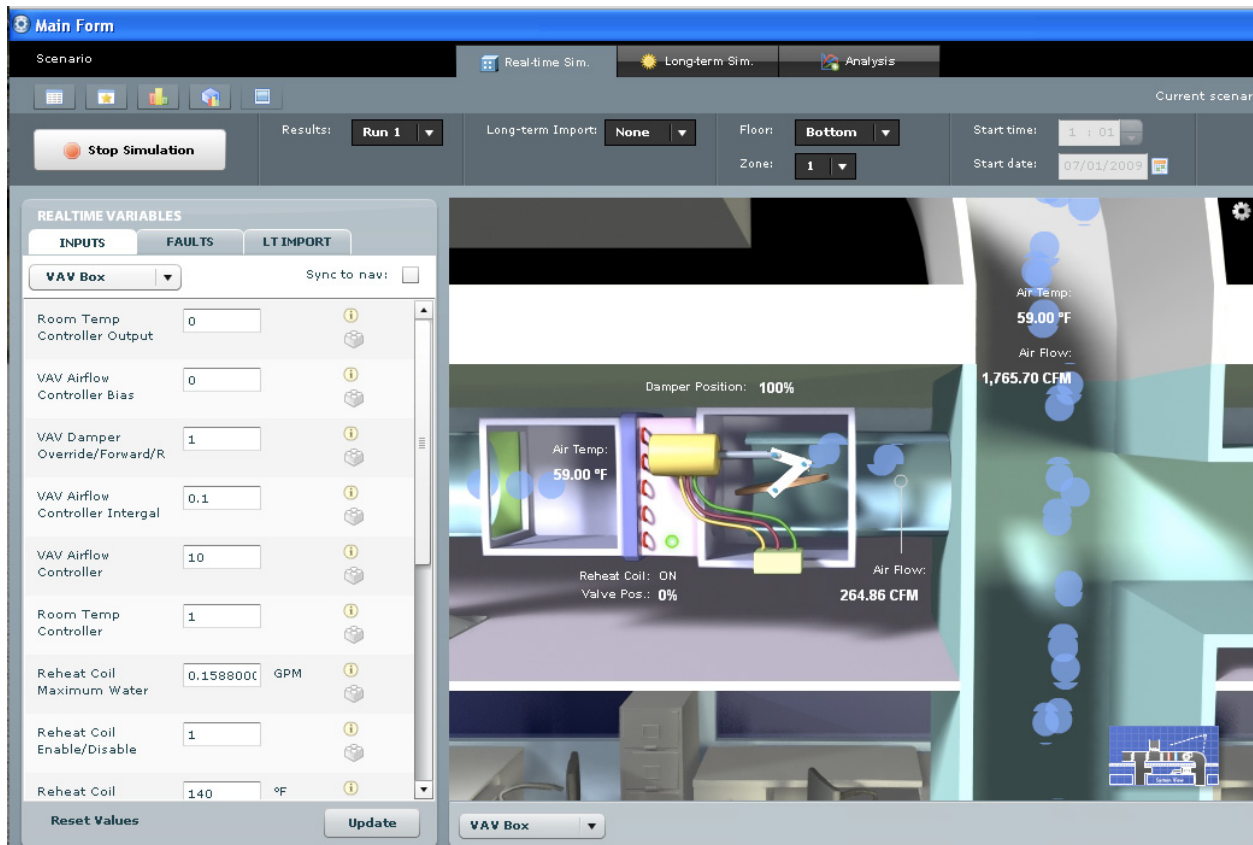


Figure A.1-7. View of VAV box

Learn HVAC versions 1.0 and 2.0 include analysis of just a single room and a single zone. Thus, the figure shows the complete VAV system and just a single VAV box serving the single zone. The VAV box includes two main components:

- A damper that controls the amount of air that will flow through this VAV box and into the room being supplied by this terminal unit.
- A heating coil that can heat the air if such heating is needed for the supply air stream to this zone or room.

Learn HVAC 3.0 is expected to include presentation of all 5 zones for a typical floor of a small to medium size office building.

A.1.7 Diffuser

Figure A.1-8 shows the view that the user sees of the diffuser, which is downstream from the VAV box and upstream from the occupied space.

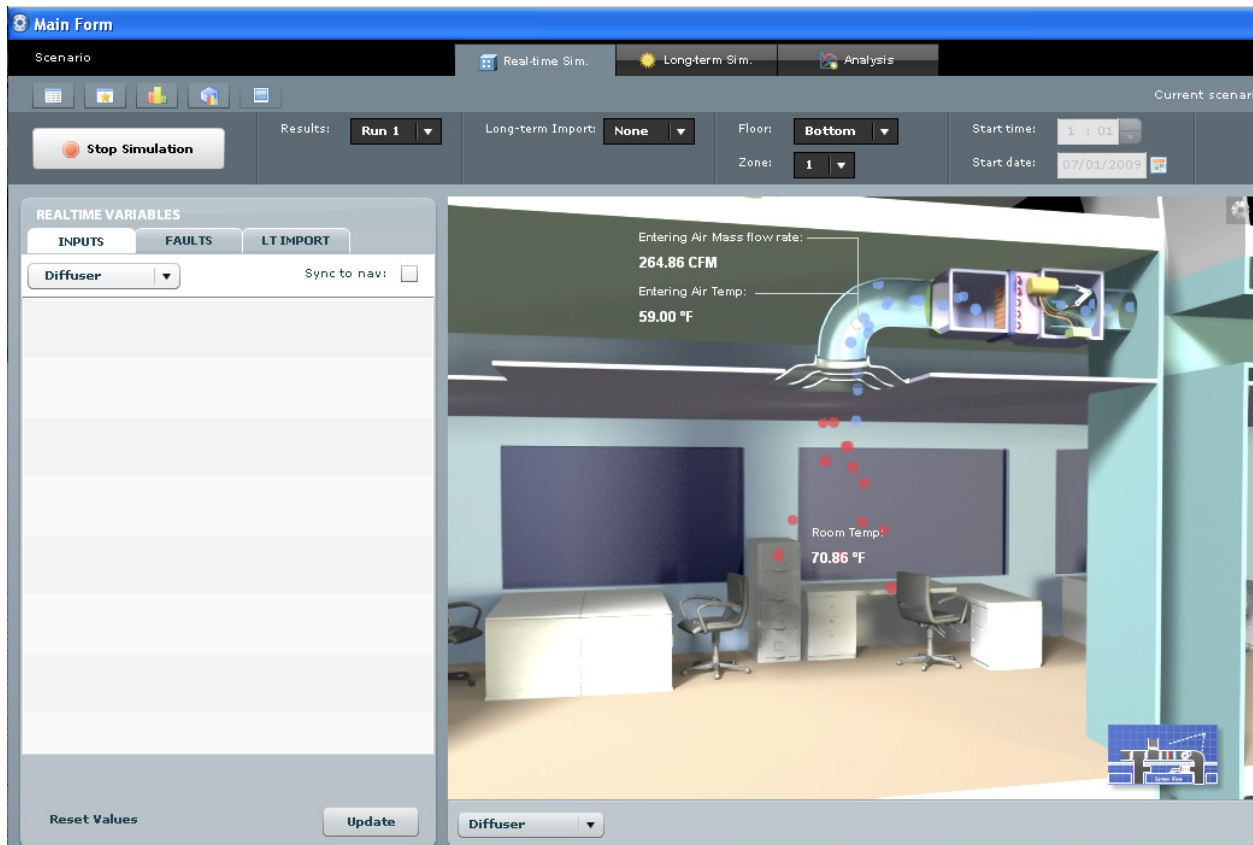


Figure A.1-8; View of diffuser

The diffuser redirects the air coming into a space into a more dispersed pattern.

A.2 New Software Modules for Learn HVAC 2.0 alpha

The project team created and added the following software modules to the existing open source software package Learn HVAC 2.0 alpha.

A.2.1 Add Energy and Peak demand calculations to Simulation Problem Analysis and Research Kernel software (SPARK) Models

The Learn HVAC 2007 contains detailed and accurate SPARK models for analyzing all main components of a typical air-handling unit for short time spans using very short time intervals, typically one second. To properly address energy issues, the project team added energy calculations to the models. Such energy issues typically use much larger time spans (e.g., diurnal, monthly, and yearly) and longer time intervals (e.g. hourly) than the existing software. The project team devised mechanisms to handle both large and small time intervals and durations as part of the pedagogical objectives, the teaching analyses, and the software-based scenarios.

The project team modified and extended existing SPARK models and sets of variables for the typical air-handling unit so that they can accept basic inputs and provide basic outputs needed

to address selected diurnal, monthly and annual energy and peak demand assessments, and to assess longer-term operations and time-intervals as well as the current short one second intervals.

The project team also refined, modified and extended the existing 2007 Flash-based Graphic User Interface (“GUI”) and related data handling capabilities of Learn HVAC to :

- Update the GUI to the newly published latest version of Flash, including Flex, in order to improve flexibility and increase execution speed;

- Refine the functionality of the 2007 version of the GUI; and

- Add new functionality to allow a user to enter or modify key energy-related input variables and to view key energy related output variables.

The project team delivered a refined and extended SPARK simulation capability plus a Flash GUI that provided links, input displays, and output displays for the new energy calculations and the larger time spans and time intervals involved (diurnal, monthly and annual).

A.2.2 Add EnergyPlus to Learn HVAC 2007 including at least one EnergyPlus prototype, with macro capabilities

The project team integrated the EnergyPlus program, including a large office prototype building description in EnergyPlus format, into Learn HVAC, along with existing macros for easily modifying the prototypes.

The project team added several new variables to the Learn HVAC system variables to permit a proof-of-concept demonstration of modifying EnergyPlus prototype building input descriptions from within the Learn HVAC program. These proof-of-concept features will, when developed further in the future, permit such prototypes to become part of standard teaching scenarios, and will greatly increase the flexibility and range of such scenarios. The project team also linked EnergyPlus output files to charting capabilities within Learn HVAC.

The project team developed extensions to the existing learn HVAC system variables, data structures, and SPARK models to handle the addition of EnergyPlus to the software environment. The team also developed refinements of the Flash Graphic User Interface (GUI) to provide links, input displays, and output displays to permit EnergyPlus analyses to be initiated from Learn HVAC, and to permit the display of selected summary EnergyPlus output results within the Learn HVAC GUI structure.

A.2.3 Add Energy Conversion Components including Water-cooled chiller and Boiler to Learn HVAC

The project team added the component and system models required to simulate a chilled water plant with cooling towers to the set of SPARK models used within the Learn HVAC framework. This is a steady state model without controls or faults.

The project team added a boiler component model and a hot water plant system model to the set of SPARK models used within the Learn HVAC framework. This is a basic steady state model without controls or faults.

The project team also added basic 3D graphics models of the chiller and boiler, and selected SPARK-driven animations, and linked these new 3D models into the Learn HVAC GUI, and provided means for users to transition to and from existing AHU components to and from each of the new components. The team also provided extensions to the existing “System Variables” to address the operation of the SPARK I-O.

A.2.4 Add New Energy Problem-Based Case Study (PBCS) Scenarios to learn HVAC

The project team developed three new problem-based case study scenarios for use with the enhanced energy-capable Learn HVAC program. This was one more scenario than required by the project scope. These new scenarios included refinements to the instructor administrative website to facilitate instructor use of the two new energy-oriented case study scenarios.

Sensor dynamics: The pressure and temperature sensors in the model have dynamics based on the formulation:

$$\dot{x} = x_0 + \int (x_{\text{steadyState}} - x) / \text{timeConstant} dt \quad (\text{Eq 3.1.1})$$

A backward-forward difference integrator is used in the current model. A generic sensor dynamics model was used for the underlying logic, with wrapper classes to construct temperature and pressure sensors (by providing appropriate ranges and time constants). For details, see the documentation for [sensor_generic_offset_bfdDynamics.cm](#), [sensor_dryBulb_generic.cm](#) and [sensor_staticPressure_generic.cm](#).

Split-Range Control of AHU: **[** Note: this has changed – the mixing box is now being controlled by a separate economizer controller. **]**

A single PI controller is used for the control of the mixing box, heating coil and cooling coil. The output from the PI controller is converted into inputs to the three components by using a split range, found in [uSplitter.cc](#) in the model. The logic is shown below. The parameters s_1 and s_2 are set by the user (with defaults of 0.67 and 0.33).

```
if (uCombined > s1) {

    // CC operation only

    uCC = (uCombined - s1) / (1.0 - s1);

    uMX = 0;

    uHC = 0;

}

else if (uCombined > s2) {
```

```

// MX operation only (OA damper)

    uCC = 0;

    uMX = (uCombined - s2) / (s1-s2);

    uHC = 0;

}

else {

    // HC operation only

    uCC = 0;

    uMX = 0;

    uHC = (s2 - uCombined) / s2;

}

```

PI Controller: The PI controller used in this model is a simple discrete-time PI controller with anti-windup and limiting of the output to the range [0,1]. The main logic, during normal operation, is as provided below:

```

e = w-y ;           // control error

p = fr*Kp*e ;       // proportional term

i = iP+fr*Ki*e*dt ; // update integral term

u = p + i + bias;    // unclipped output

if (u > 1.0) {        // limit output to 0-1

    i = i - (u-1.0);

    u = 1.0;

} else if (u < 0.0) {

    i = i - u;

```

```

        u = 0.0;

    }

```

For details, see the documentation for [PI.cc](#).

A.3 Refined SPARK component simulation models

During this project a number of refinements have been made to the component simulation models. The new, 2010 versions are described below.

A.3.1 Mixing box and economizer

During this project the mixing box simulation model technical details were refined and documented. The results are described below.

A minimum outside air (OA) fraction is included as a parameter to the model. The current outside air fraction is controlled by a minimum 20 percent outside air damper setting. Note that a damper setting of 20 percent does not necessarily mean that the resultant percentage of outside air is also 20 percent.

Technical details of the mixing box model: The mixing box model calculates the mixed air temperature and humidity given:

- the return air temperature (RAT) and humidity,
- the outside air temperature (OAT) and humidity,
- the supply air flow rate and
- the damper position signals for the outside air (OA) and the exhaust air (EA).

The governing equations are the mixing equations below (which use dry bulb temperature in the place of enthalpy as the conserved quantity – a slight approximation that saves computation time).

$$T_{Mix} = \frac{(T_{Out} * OA_{PosDamperReal} + T_{Ret} * RA_{PosDamperReal})}{(OA_{PosDamperReal} + RA_{PosDamperReal})} \quad (Eq\ 2.1.1)$$

$$w_{Mix} = \frac{(w_{Out} * OA_{PosDamperReal} + w_{Ret} * RA_{PosDamperReal})}{(OA_{PosDamperReal} + RA_{PosDamperReal})}; \quad (Eq\ 2.1.2)$$

For further technical details about the mixing box model, see the documentation for [mix.cc](#).

Input Variables: Initial conditions for the following mixing box input variables are specified in each scenario used within Learn HVAC

Faults: The mixing box model also includes parameters for various faults, including stuck or leaking dampers.

A.3.2 Filter

The filter model currently only performs a simple calculation of the pressure drop across the filter.

$$\text{filterPressureDrop} = c * \text{massFlowRate}^2 \quad (\text{Eq. 2.2.1})$$

where

c is an empirical constant, set to 0.01 within the model code.

Note that this model is essentially acting as a placeholder at present, since the pressure drops throughout the system are not being calculated explicitly.

For details, see the documentation for Filter.cc.

Filter Input Variables: There are currently no input variables specified for the filter.

Filter Faults: The filter model also includes parameters for two faults:

a partly clogged filter (which increases the pressure drop); and

a bad sensor (which introduces an offset in the sensed pressure drop).

A.3.3 Heating coil

During this project, the heating coil simulation model technical details were refined and documented during this project. The results are described below.

Heating Coil Technical Details: The heating coil is modeled as a cross flow heat exchanger, with a dry coil assumption. The underlying heat exchanger model is based on the ASHRAE Toolkit DRYCOIL model, and uses an Ntu-effectiveness calculation. The essential equations for the heat exchanger are as follows:

$$\text{capAir} = \text{mAirEnt} * (\text{CpAir} + \text{wAirEnt} * \text{CpVap}) \quad (\text{Eq 2.3.1})$$

$$\text{capLiq} = \text{mLiq} * \text{CpLiq} \quad (\text{Eq 2.3.2})$$

$$Q = \text{capAir} * (\text{TAirEnt} - \text{TAirLvg}) \quad (\text{Eq 2.3.3})$$

$$\text{wAirLvg} = \text{wAirEnt} \quad (\text{Eq 2.3.4})$$

$$\text{heatex}(\text{capLiq}, \text{TLiqEnt}, \text{capAir}, \text{TAirEnt}, \text{UA}, \text{ConfigHX}, \text{TLiqLvg}, \text{TAirLvg})$$

(Eq 2.3.5)

The last equation is a reference to the heat exchanger model in drcc1u.cm in the standard SPARK hvac toolkit (hvactk).

The coil is controlled by modulating the liquid flow with a valve. A three way valve model is used includes parameters for modeling faults, particularly valve leakage.

For details, note the following model structure and see the documentation for the components: the main class that ties the heating coil model together is heatingcoil.cm; it calls upon a number of other classes, including the heat exchange model drcc1u.cm and the valve model valve.cc. The details of the heat exchange model can be found by following through the line of references from drcc1u.cm to htxc1u.cm to effc1u.cc.

A.3.4 Cooling coil

During this project, the cooling coil simulation model technical details were refined and documented. The results are described below.

Cooling Coil Technical Details: The cooling coil roughly follows the ASHRAE Toolkit CCSIM model, although not precisely. Both dry and wet coil models are run in parallel, for the given air stream, and a switch selects between the two sets of outputs depending on the entering dw point, surface and liquid temperatures, and the loads calculated by the two models. The dry coil model uses the same counter flow heat exchanger model that is used in the heating coil (based on the ASHRAE Toolkit DRYCOIL model). The wet coil model uses a counter flow heat exchanger model of cooling and dehumidification that assumes that the entire metal surface is wetted by condensate (based on the ASHRAE Toolkit WETCOIL model).

The main equations at the highest level in this model are noted as follows:

Wet Coil Equations

$$1/UTotD = 1/UExtW + 1/UIntW$$

$$UATotD = UTotD * ATot$$

$$UAEExtW = UExtW * ATot$$

$$UAIIntW = UIntW * ATot$$

$$s = \text{if}(qDry < qWet)$$

$$\quad \text{if}(TDp < TLiq)$$

$$\quad \quad 0;$$

$$\quad \text{else}$$

$$\quad \quad 1;$$

```

else
    if(TDp < TSurf)
        0;
    else
        1;

TAirLvg = s ? TAirLvgW : TAirLvgD
wAirLvg = s ? wAirLvgW : wAirLvgD
TLiqLvg = s ? TLiqLvgW : TLiqLvgD
qTot = s ? qTotW : qTotD
qSens = s ? qSensW : qSensD
mAirLvg = mAirEnt

```

Similar to the heating coil, the cooling coil is controlled by modulating the liquid flow with a valve. The valve being used for the cooling coil is a two-way valve. The valve model includes parameters for modeling faults, particularly valve leakage.

For details, note the following model structure and see the documentation for the components: the main class that ties the cooling coil model together is `coolingcoil.cm`, which in turn calls the key model `ccsim.cm`, along with a valve model `valve.cc`, the `UASplit.cc` model, and a model for cooling coil faults; `ccsim` in turn calls upon a number of other classes, including the dry-coil heat exchange model `drcctr.cm` and the wet-coil heat exchange model `wtcctr.cm`.

A.3.5 Fan

During this project, the fan simulation model technical details were refined and documented. The results are described below.

Fan Technical Details: The fan model calculates the pressure gain, power consumption and outlet air temperature and humidity, given a control signal, an airflow rate and the inlet air temperature and humidity. The main equations are as given below

$$\text{powerShaft} = (\text{mAir}/\text{RHO_AIR}) * \text{pFan} / \text{effShaft} \quad (\text{Eq 2.5.1})$$

$$\text{powerTot} = \text{powerShaft} / \text{effMot} \quad \text{Eq 2.5.2}$$

$$\text{qLoss} = (\text{powerShaft}) + (\text{powerTot} - \text{powerShaft}) * \text{motFrac} \quad (\text{Eq 2.5.3})$$

$$\text{TAirLvg} = \text{TAirEnt} + \text{qLoss} / (\text{CP_AIR} * \text{mAir}) \quad (\text{Eq 2.5.4})$$

$$\text{wAirLvg} = \text{wAirEnt} \quad (\text{Eq 2.5.5})$$

$$\text{pStat} = \max(0, (\text{pFan} - \text{CRes} * \text{mAir} * \text{mAir})) \quad (\text{Eq 2.5.6})$$

A.3.6 VAV box with reheat

During this project, the VAV box simulation model technical details were refined and documented. The results are described below.

VAV box Technical Details: The VAV box has two sub-component models: a damper model and a heating coil model.

The damper model calculates the pressure drop across the damper and the air flow rate, given a control signal and considering a number of possible faults.

The heating coil model, used for reheat within the VAV box, uses the same model as described above for the heating coil.

For details, see the documentation for VAV_damper.cc, VAV_damper_min.cc and VAV_control.cc. The latter converts an overall control signal for the box into control signals for the heating coil and damper position.